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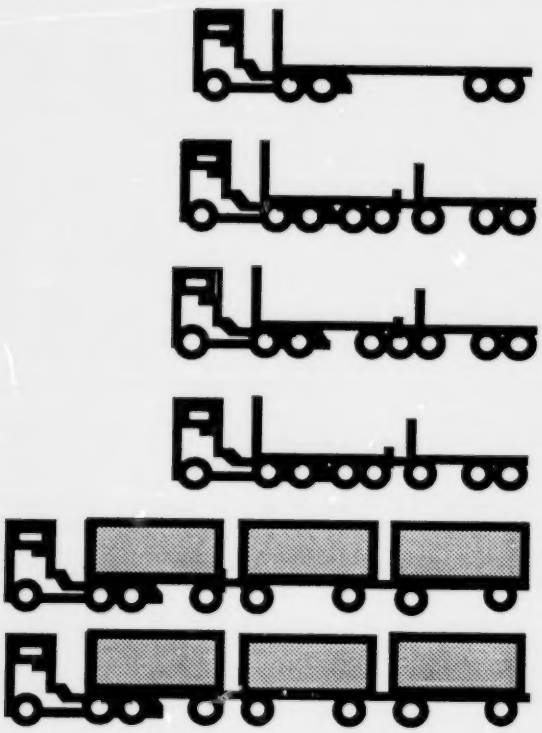
Summary of Tests of Baseline Vehicle Performance



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Summary of Tests of Baseline Vehicle Performance

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Head,
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Abstract:
A substantial program of full-scale heavy truck dynamic testing was undertaken in 1985 on behalf of the CCMTA/RTAC Vehicle Weights and Dimensions Study by the Ontario Ministry of Transportation and Communications.

This report summarizes tests of six baseline vehicle configurations: a tractor-semitrailer; A-, B-, and C-train doubles; and A- and C-train triples configurations.

Key Words: truck testing, offtracking, truck turning, air brake system, braking, truck dynamic tests, rearward amplification, rollover, lane change, tilt test

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ABSTRACT

A substantial program of full-scale heavy truck dynamic testing was undertaken in 1985 on behalf of the CCMTA/RTAC Vehicle Weights and Dimensions Study by the Ontario Ministry of Transportation and Communications.

This report summarizes tests of six baseline vehicle configurations: a tractor-semitrailer; A-, B-, and C-train doubles; and A- and C-train triples combinations.

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EXECUTIVE SUMMARY

The effects of weight and dimension parameters on heavy truck stability and control and on pavement response are being examined in the CCMTA/RTAC Vehicle Weights and Dimension Study. The objective of the study is to compile technical information to provide a basis for the provinces to amend their truck weight and dimension regulations. The goal is to simplify interprovincial trucking through greater uniformity in these regulations.

A baseline vehicle was selected to represent each of six major configurations: the tractor-trailer; A-, B- and C-train doubles; and A- and C-train triples. The Ontario Ministry of Transportation and Communications subjected each of these baseline vehicles to a standard series of tests for turning; the brake system; lateral/directional and roll stability; trailer swing; and a demonstration of straight-line braking.

The primary objective of the test program was to assemble a body of technical and visual data that described the stability and control characteristics of the baseline vehicles with respect to certain performance measures. These tests would be used as a background to complement the findings of a comprehensive computer simulation that was used to evaluate variations in weight, dimension, and equipment for the six configurations.

Vehicle turning performance depends primarily on trailer length and the number of trailers. It is not strongly dependent on the method of hitching. As trailer length or number of trailers increases, so does the space required to make turns.

Air brake system performance depends upon the number of vehicle units and selection and installation of components.

Lateral stability is strongly dependent upon vehicle configuration. The semi was the most stable, doubles were more stable than triples of similar configuration, and B- or C-trains were more stable than the A-train. This ranking follows the number of articulation points -- the more articulation points, the lower the stability.

EXECUTIVE SUMMARY (CONT'D)

Static roll stability is essentially independent of vehicle configuration where vehicles have the same suspension, axle load, and centre of gravity height.

An extensive computer simulation using measured test inputs and actual vehicle properties showed that responses of all vehicles could be predicted quite well both for individual runs and as a trend over a number of runs.

The specific results presented here apply to the vehicles tested for the particular test conditions. Results different in some respect might be expected for other vehicles or test conditions.

1/ INTRODUCTION

The effects of weight and dimension parameters on heavy truck stability and control and on pavement response are being examined in the CCMTA/RTAC Vehicle Weights and Dimensions Study. The objective of the study is to compile technical information that, with an earlier study of the effects of heavy trucks on bridge loading [1], would provide a basis for the provinces to amend their truck weight and dimension regulations. The goal is to simplify interprovincial trucking through greater uniformity in these regulations.

The truck population of Canada was surveyed [2], and six generic families were defined, based on the number of trailers and hitching methods. One vehicle in common use in at least some provinces was selected as representative of each family and designated as the baseline vehicle configuration. Each baseline vehicle served as a yardstick against which variations in weight, dimension, or equipment were to be evaluated by means of a comprehensive series of computer simulations. The Ontario Ministry of Transportation and Communications (MTC) was asked to test the six baseline vehicles as part of its contribution to the study.

The primary objective of the test program was to assemble a body of technical and visual data that described the stability and control characteristics of the baseline vehicles with respect to certain performance measures. These tests would be used as a background to complement the findings of the computer simulation. Test manoeuvres were conducted to examine the following:

- turning performance;
- the air brake system;
- lateral/directional stability characteristics of an empty vehicle on a low-friction surface, with and without braking;
- lateral/directional response characteristics of a loaded vehicle on a high-friction surface;
- steady-state roll characteristics of a loaded vehicle on a high-friction surface;
- dynamic stability characteristics of a loaded vehicle on a high-friction surface;
- trailer sway.

A secondary objective was to conduct computer simulations using the measured test inputs and actual vehicle unit properties to demonstrate that simulation can represent vehicle responses for a wide range of

vehicles and test manoeuvres.

This report presents a summary of the baseline vehicle tests. It will refer to reports describing procedures common to test of all six vehicles [3], the test results of the six baseline vehicles [4-9], and to a report describing the computer simulation results in comparison with the test data [10].

2/ TEST VEHICLES

The set of vehicles to be tested was defined and provided to MTC by the study.

The tractor-trailer family was represented by a 45 ft (13.72 m) semi. The A-, B-, and C-train doubles families were all represented by 8-axle combinations with two trailers, each with a bed length of 7.92 m (26 ft). Two triples families, the A- and C-train, were represented by 8-axle combinations with three 8.53 m (28 ft) trailers. All equipment was typical of that used in at least one region of the country. The 45 ft (13.72 m) semi is a utility vehicle. The three doubles are all used for heavy haul and are closely comparable with each other from a usage standpoint. They are not comparable to the semi, because all provinces allow a higher gross weight for a combination with a greater number of axles. An operator whose primary business is moving heavy loads will always select the vehicle with the highest possible gross weight over a 5-axle semi. The triples are used only by special permit at relatively low gross weights, primarily for volume-limited cargo. While they are comparable with each other, they are not comparable either with the semi or the doubles by current usage. Clearly, if the triples were permitted higher gross weights than the doubles, they might be used in heavy-haul applications.

The test vehicle consisted of the MTC Freightliner [3] and the trailer or trailer combination being tested. A 1976 Freightliner 6x4 was used for all except two turning tests. The MTC Freightliner, seen in Figure 1, has been used in many previous test programs and was already fully instrumented for the requirements of these tests. It was a cab-over-engine type with integral sleeper, powered by a Detroit Diesel V-12 engine rated at 465 bhp at 2100 rpm. The front axle was rated at 8182 kg (18 000 lb), and the tandem drive axles used a Hendrickson RTE-440 walking beam suspension rated at 20 000 kg (44 000 lb). The wheelbase was 3.50 m (138 in), the tandem axle spread was 1.83 m (72 in), and the drive axle wheel track was 2.44 m (96 in). The fifth wheel was installed 0.20 m (8 in) forward of the midpoint of the drive tandem. The normal operating weight of the Freightliner was about 9790 kg (21 540 lb), including driver and typical quantities of fluids. The Freightliner front axle used Michelin XZA radial tires, load range G, size 11R24.5, and the drive axles used Michelin XM+S4 radial tires, load range G, size 11R24.5. The Freightliner is somewhat atypical of late-model tractors used in interprovincial trucking, where the typical front axle rating is

5455 kg (12 000 lb), drive tandem spread is 1.52 m (60 in), and weight is7730 to 8409 kg (17 000 to 18 500 lb) [2].

A 1974 4x2 International Loadstar was used for two turning tests because it allowed the Freightliner to be available for other tests and vehicle preparation activities critical to the test schedule. This tractor is not typical at all of tractors which would haul the test trailers in interprovincial trucking. However, with a 3.81 m (150 in) wheelbase, and a fifth wheel 0.015 m (6 in) forward of the drive axle, its turning characteristics were regarded as sufficiently close to those of the Freightliner that the substitution was acceptable. Other specifications of this tractor are irrelevant to the test program, so are not presented.

No modifications were made to any equipment except for purposes of attachment of test equipment, which had no effect on the operation of the vehicle, though unit weights and polar moments of inertia were affected.

The empty weight of the vehicle as tested exceeds that which would normally be seen on the highway, because the tractor is considerably heavier than late-model equipment and because of the weight of test equipment installed, particularly the outriggers. The study set a target load of 8000 kg (17 600 lb) for all axles except for the steer axle.

2.1/ 45 ft Semi

The test vehicle consisted of the MTC Freightliner and a 45 ft (13.72 m) tandem-axle semitrailer. The combination is typical of equipment used in Atlantic and Western Canada and the US. Semitrailers used in Central Canada now typically have a tandem-axle spread of 1.83 m (72 in) or more, compared with the 1.37 m (54 in) of this trailer.

The trailer was manufactured by RAM Highway Trailers of Canada in June 1981 and bore the serial number 381-13648. The trailer had a nominal length of 13.72 m (45 ft) and a nominal width of 2.44 m (96 in). Suspension was a four-spring leaf system with torque rods and equalizers. The spring centre width was 0.96 m (38 in), and the track width was 2.44 m (96 in). The trailer was rated at 8000 kg/axle (17 600 lb/axle). The axle spacing was 1.37 m (54 in). The combination had an overall length of 17.17 m (58.30 ft).

The test vehicle is shown in Figure 1, in test condition with outriggers installed. The dimensions of the test vehicle are presented in Figure 2.

Empty weight of the combination in test condition was 18 299 kg (40 260 lb). Concrete blocks were used to obtain a loaded weight of 31 205 kg (68 650 lb). Axle loads in these conditions are given in Table 1. The legal gross weight for the vehicle tested varies between 36 500 and about 41 000 kg (80 300 and 90 200 lb), depending upon the province.

Table 1/ Axle Loads, 45 ft Semi

Axle No.	Empty		Loaded	
	(kg)	(lb)	(kg)	(lb)
1	5 009	11 020	5 118	11 260
2	4 209	9 260	6 114	13 450
3	3 791	8 340	6 114	13 450
4	2 472	5 440	6 882	15 140
5	2 818	6 200	6 977	15 350
Total	18 299	40 260	31 205	68 650

The height of the centre of gravity of the empty trailer sprung mass was estimated as 0.240 m (9.44 in) below the top of the floor. The centre of gravity height was estimated as 0.168 m (6.61 in) above the top of the floor in the loaded condition.

2.2/ A-Train Double

The test vehicle consisted of the MTC Freightliner and two tandem-axle flatbed semitrailers with a single-axle A-type converter dolly. The combination is typical of equipment used in all regions of Canada, except the Atlantic provinces.

The trailers were manufactured by Fruehauf in Winnipeg and were model PB-F2-26-102-SF, with serial numbers DXT2796-08 and DXT2796-06. Each trailer had a nominal length of 7.93 m (26 ft) and a nominal width of 2.44 m (96 in). Each had two axles spaced 1.24 m (49 in) apart and suspended from a Reyco 21B four-spring leaf system with torque rods and equalizer arms. The spring centre spacing for each trailer was 0.96 m (38 in), and the track width was 2.44 m (96 in). The A-dolly comprised a standard A-dolly frame and a Reyco 21B two-spring leaf suspension system with a torque rod. The A-dolly had a spring centre width of 0.97 m (38.5 in), and the track width was 2.44 m (96 in). The fifth-wheel-to-hitch distance was 2.14 m (7 ft). The combination had an overall length

of 21.07 m (69.13 ft).

The test vehicle is shown in Figure 3, in test condition with outriggers installed. The dimensions of the test vehicle are presented in Figure 4. Empty weight of the combination in test condition was 24 368 kg (53 610 lb). Concrete blocks were used to obtain a loaded weight of 47 699 kg (104 940 lb). Axle loads in these conditions are given in Table 2. Both trailers were loaded in the same fashion. The legal gross weight of the vehicle tested varies between 52 800 and 61 600 kg (116 160 and 135 520 lb), depending on the province.

Table 2/ Axle Loads, A-Train Double

Axle No.	Empty		Loaded	
	(kg)	(lb)	(kg)	(lb)
1	5 082	11 180	5 127	11 280
2	3 845	8 460	5 327	11 720
3	3 027	6 660	5 486	12 070
4	2 205	4 850	5 250	11 550
5	2 277	5 010	6 882	15 140
6	3 323	7 310	7 400	16 280
7	2 950	6 490	6 936	15 260
8	1 659	3 650	5 291	11 640
Total	24 368	53 610	47 699	104 940

The height of the centre of gravity of the empty trailer sprung mass was estimated as 0.374 m (14.7 in) below the top of the floor. The centre of gravity height was estimated as 0.202 m (8 in) above the top of the floor in the loaded condition.

2.3/ B-Train Double

The test vehicle consisted of the MTC Freightliner and a B-train double trailer combination with a centre triple axle and rear tandem axle. The combination is typical of equipment used in Central Canada in heavy-haul applications.

The trailers were manufactured by Pullman Trailmobile Canada in February 1980 and bore serial number 2.80.1110.1028.002. Both trailers had a nominal length of 7.92 m (26 ft) and a nominal width of 2.44 m (96 in).

The lead trailer was provided with a triple-axle unit with an axle spacing of 1.52 m (60 in) and a Reyco six-spring suspension system with torque rods and equalizers. It had a fifth wheel mounted above the rear axle of the triple-axle unit. The tandem-axle rear trailer had an axle spacing of 1.79 m (70.5 in) and a Reyco four-spring suspension system with torque rods and equalizers. On both trailers, the spring centre spacing was 0.96 m (38 in); the nominal track width, 2.44 m (96 in); and the axle rating, 9616 kg (21 155 lb). The combination had an overall length of 22.1 m (72.5 ft).

The test vehicle is shown in Figure 5, in test condition with outriggers installed. The dimensions of the test vehicle are presented in Figure 6. Empty weight of the combination in test condition was 26 155 kg (57 540 lb). Concrete blocks were used to obtain a loaded weight of 52 764 kg (116 080 lb). Axle loads in these conditions are given in Table 3. The legal gross weight of the vehicle tested is 56 600 kg (124 560 lb) in Quebec and 60 500 kg (133 100 lb) in Ontario, and would be about 52 000 kg (114 400 lb) where permitted in the prairie provinces.

Table 3/ Axle Loads, B-Train Double

Axle No.	Empty		Loaded	
	(kg)	(lb)	(kg)	(lb)
1	4 650	10 230	4 991	10 980
2	3 996	8 790	6 082	13 380
3	3 500	7 700	5 723	12 590
4	3 386	7 450	7 864	17 300
5	2 918	6 420	7 827	17 220
6	2 664	5 860	7 232	15 910
7	3 077	6 770	7 536	16 580
8	1 964	4 320	5 509	12 120
Total	26 155	57 540	52 764	116 080

The height of the centre of gravity of the empty trailer sprung mass was estimated as 0.374 m (14.7 in) below the top of the floor. The centre of gravity height was estimated as 0.217 m (8.5 in) above the top of the floor in the loaded condition.

2.4/ C-Train Double

The test vehicle consisted of the MTC Freightliner and two tandem-axle flatbed semitrailers with a single-axle B-type converter dolly. The combination is typical of equipment used in provinces where C-train double trailer combinations operate.

The trailers were the same as those used in the A-train double (Section 2.3), but in the reverse order. The B-dolly was made up from the ASTL SSD frame, used in previous tests [11], and a Sauer model RLZ10041 self-steering axle rated at 10 000 kg (22 000 lb) and placarded for a speed of 80 km/h. Suspension was a Reyco two-spring leaf system with a torque rod. The B-dolly had a spring centre width of 0.76 m (30 in), and the track width was 2.44 m (96 in). The fifth-wheel-to-hitch distance was 1.98 m (6.5 ft). The combination had an overall length of 20.97 m (68.8 ft).

The test vehicle is shown in Figure 7, in test condition with outriggers installed. The dimensions of the test vehicle are presented in Figure 8. Empty weight of the combination in test condition was 24 196 kg (53 230 lb). Concrete blocks were used to obtain a loaded weight of 48 668 kg (107 070 lb). Axle loads in these conditions are given in Table 4. Both trailers were loaded in the same fashion. The legal gross weight of the vehicle tested varies between 52 800 and 61 600 kg (116 160 and 135 520 lb), depending on the province.

Table 4/ Axle Loads, C-Train Double

Axle No.	Empty		Loaded	
	(kg)	(lb)	(kg)	(lb)
1	4 832	10 630	5 127	11 280
2	3 700	8 140	5 445	11 980
3	3 218	7 080	5 464	12 020
4	2 073	4 560	5 664	12 460
5	2 355	5 180	6 536	14 380
6	3 518	7 740	7 727	17 000
7	2 445	5 380	6 814	14 990
8	2 055	4 520	5 891	12 960
Total	24 196	53 230	48 668	107 070

The height of the centre of gravity of the empty trailer sprung mass was estimated as 0.374 m (14.72 in) below the top of the floor. The centre of gravity height was estimated as 0.202 m (8 in) above the top of the floor in the loaded condition.

2.5/ A-Train Triple

The test vehicle consisted of the MTC Freightliner and three single-axle van-type semitrailers with single-axle A-type converter dollies. The combination is typical of equipment used in provinces where triple trailer combinations operate under special permit. The equipment was inspected before the test by a representative of the owner on behalf of the Canadian Trucking Association, with no deviations from specificationsreported.

The trailers and dollies were brand new. They were manufactured by Trailmobile in February 1985. The trailers had serial numbers 2TCH281B6EA303117, 2TCH281B93A303130, and 25CH281B93A303127 and fleet numbers 7794, 7807, and 7804, from front to rear, respectively. The A-dollies had serial numbers 2TCT101AXEA303207 and 2TCT101A3EA303209 and fleet numbers 0747 and 0745 for front and rear, respectively.

Each trailer had a nominal length of 8.53 m (28 ft) and a nominal width of 2.59 m (102 in). Each trailer had a tapered nose section and a 1.22 m (4 ft) kingpin set back so that they could also be operated as a legal doubles combination in some provinces. The trailers were insulated, and a propane heater was installed at the front near the roof. The trailer suspension had a single tapered leaf spring and was rated at 9616 kg (21 155 lb). The spring spread was 1.09 m (43 in), and the track width was 2.59 m (102 in). The spring lash space was 38 to 41 mm (1.5 to 1.63 in). The trailers were equipped with an air-actuated no-slack pintle hook. The dollies had the same suspension as the trailers, a drawbar length of 2.13 m (84 in), and a fifth wheel set 25 mm (1 in) forward of the axle centreline. The combination had an overall length of 31.08 m (102 ft).

The test vehicle is shown in Figure 9, in test condition with outriggers installed. The dimensions of the test vehicle are presented in Figure 10. Empty weight of the combination in test condition was 33 087 kg (72 790 lb). Concrete blocks were used to obtain a loaded weight of 55 942 kg (123 070 lb). Axle loads in these conditions are given in Table 5. The loaded weight is somewhat greater than that

allowed by provinces where this combination runs under special permit. Typical loaded weights on the highway for such combinations are often much less than that allowed, by the nature of the cargo carried by the vehicle. All three trailers were loaded in the same fashion, consistent with normal practice. The tractor drive axles, therefore, were loaded less than each trailer axle, because their combined load was much less than 12 000 kg (26 400 lb) because of the empty vehicle.

Table 5/ Axle Loads, A-Train Triple

Axle No.	Empty		Loaded	
	(kg)	(lb)	(kg)	(lb)
1	4 864	10 700	5 286	11 630
2	3 945	8 680	5 914	13 010
3	3 705	8 150	5 168	11 370
4	4 177	9 190	7 800	17 160
5	4 091	9 000	8 073	17 760
6	4 377	9 630	7 964	17 520
7	3 855	8 480	8 005	17 610
8	4 073	8 960	7 732	17 010
Total	33 087	72 790	55 942	123 070

The height of the centre of gravity of the empty trailer sprung mass was estimated as 0.405 m (16 in) above the top of the floor. The centre of gravity height was estimated as 0.327 m (13 in) above the top of the floor in the loaded condition.

2.6/ C-Train Triple

The test vehicle consisted of the MTC Freightliner and three single-axle van-type semitrailers with single-axle B-type converter dollies. The combination is typical of equipment used in provinces where triple trailer combinations operate under special permit.

The trailers were the same as those used for the A-train triple, described in Section 2.5. The B-dolly of the C-train double, described in Section 2.4, and another identical one, were used to couple the trailers.

The test vehicle is shown in Figure 11, in test condition with outriggers installed. The dimensions of the test vehicle are presented in Figure 12. Empty weight of the combination in test condition was 33 997 kg (74 790 lb). Concrete blocks were used to obtain a loaded weight of 56 386 kg (124 050 lb). Axle loads in these conditions are given in Table 6. All three trailers were loaded in the same fashion, consistent with normal practice. The tractor drive axles, therefore, were loaded less than each trailer axle, because their combined load was much less than 12 000 kg (26 400 lb) because of the empty vehicle.

Table 6/ Axle Loads, C-Train Triple

Axle No.	Empty		Loaded	
	(kg)	(lb)	(kg)	(lb)
1	5 014	11 030	5 286	11 630
2	4 114	9 050	5 914	13 010
3	3 523	7 750	5 168	11 370
4	4 305	9 470	7 800	17 160
5	4 286	9 430	8 295	18 250
6	4 409	9 700	7 964	17 520
7	3 223	9 290	8 227	18 100
8	4 123	9 070	7 732	17 010
Total	33 997	74 790	56 386	124 050

3/ TEST PROGRAM

3.1/ Test Facilities

Empty vehicle, low-friction surface tests were conducted at the Ministry of Transportation and Communications (MTC) Commercial Vehicle Test Facility (Centralia). This test facility is located at Huron Industrial Park, Centralia, 45 km north of London, Ontario. The test area includes a low-friction surface 200 m long with a wet skid number of about 18 to 24. A sprinkler system is used for continuous wetting of this surface. The test facility also has about 2000 m^2 of work space which was used for vehicle preparation and storage. It includes basic shop facilities, an electronics lab, office space, and a ground station for data acquisition and processing [3].

Loaded-vehicle, high-friction surface tests were conducted at the Transport Canada Motor Vehicle Test Centre, located at Blainville, Quebec, 35 km north of Montreal [3]. This facility was made available for the study by Transport Canada. In addition, tilt tests were conducted on the 45 ft (13.72 m) semi and the three doubles by others, using a tilt table installed for the study [12].

3.2/ Vehicle Preparation

The test trailers were equipped with the following:

- new tires
- outriggers
- safety cables
- instrument packages
- load

The trailers and dollies were fitted with new Michelin XZA radial tires, in load range H and size 11R22.5. These tires were run a nominal distance before any testing and were then, subsequently, used for all tests. Tire pressure was set cold at 689 kPa (100 psi), which is the manufacturer's recommended value for full load on all tires. This was used for all tests and represents the common operating practice of not reducing tire pressure when running empty.

Detachable beam-type underslung outriggers were specially designed, and three sets were fabricated for these tests, as can be seen in Figure 9. The outriggers were set with a ground clearance of 0.25 to 0.30 m, which

corresponds to a trailer roll angle of 6 to 7° at outrigger touchdown. Some local strengthening of flatbed trailers was conducted so that the structure could resist touchdown loads without permanent deformation.

High-speed dynamic testing of combination vehicles on a low-friction surface carries the hazard of tractor or dolly jackknife, or trailer swing. To prevent damage from such loss of control, safety cables were installed between each consecutive pair of vehicle units to limit articulation angles to about 20°.

Each vehicle was tested nominally empty, without payload, but equipped with instrumentation, outriggers, and safety cables. Each trailer therefore weighed about 1500 to 1800 kg (3300 to 4000 lb) more than it would on the highway.

Each vehicle was also tested at one nominal gross weight. This gross weight was achieved by loading trailers with concrete blocks, weighing about 936 kg (2060 lb) each. Blocks were tightly secured with chains.

Before testing, the vehicle was assembled in its test configuration, and the following additional measures were taken:

- The vehicle was checked for general mechanical fitness.
- Brake slack was checked and adjusted as necessary.
- Tire inflation pressure was set.
- Relevant vehicle dimensions were measured.
- The vehicle was weighed by axle, empty and loaded.
- Detailed measurements and an inventory of trailer structural numbers, fittings, and other components were made.
- Instrumentation was installed, as described in Section 5.2.
- Still photographs and video were taken of the vehicle as a whole, parts thereof, and instrumentation installations.

Detailed descriptions of vehicle preparation are presented elsewhere [3].

3.3/ Instrumentation

The MTC Freightliner has been used in many previous test programs. As a consequence, it was already equipped to measure the following driver inputs and vehicle responses:

- road wheel steer angle;
- speed;

- distance travelled;
- brake on/off;
- brake treadle valve pressure;
- brake chamber pressures;
- roll, pitch, and yaw angles;
- roll, pitch and yaw rates;
- longitudinal, lateral, and vertical accelerations measured from an inertial platform;
- lateral load at the fifth wheel;
- an optical sensor for precise speed and position measurements;
- others, not required for this test program, such as steering wheel angle and rate, other wheel speeds, etc.

The tractor was equipped to control the instrumentation either by an automatic or a manual start that uncaged the gyro package, initialized the distance counter, commanded the data acquisition system through a calibration sequence, and finally returned it to data status. The automatic start was triggered by means of a downward facing optical sensor mounted beneath the tractor, which responded to a highly reflective patch of tape placed on the ground a suitable distance ahead of the point where the test manoeuvre was to be made. This meant the data sequences for similar runs were similar, which simplified the development of computer data processing. Since the optical sensor would trigger on any light colour, it was normally inactive and was armed by the driver on the approach just before the start patch.

Each trailer was instrumented to measure the following basic responses:
- articulation angle
- lateral acceleration
- roll angle
- outrigger touchdown
- brake chamber pressures

A single package containing the accelerometer and roll gyro, signal conditioning, multiplex, and power supply contained the bulk of the instrumentation for each trailer. This package was mounted on the deck of the trailer midway between the kingpin and the centre of the trailer axles.

Each A-dolly was instrumented to measure the hitch articulation angle. Each B-dolly was instrumented to measure its axle steer angle by means of a rotary potentiometer. Each dolly also had an accelerometer installed to measure lateral acceleration at a point close to the trailer kingpin.

A pressure transducer was also installed in a brake chamber for the brake tests.

Detailed descriptions of instrumentation are described elsewhere [3].

3.4/ Definition of Tests

The tests and demonstration conducted on all vehicles are broken down into four categories:

1/ Stationary
- Air brake system
- Tilt test

2/ Low-Speed Turns
- Steady-state offtracking
- Right-hand turn
- Channelized right turn

3/ Low-Friction Dynamic, Empty Vehicle
- Straight-line braking demonstration
- Evasive manoeuvre

4/ High-Friction Dynamic, Loaded Vehicle
- Sinusoidal steer
- Lane change
- Straight-line driving
- Steady circular turn

The following subsections present the rationale for each test and outline the procedure followed. Detailed procedures are presented elsewhere [3].

For all driving tests where a sequence of runs at increasing speeds was required, speeds were selected that resulted from the driver using full throttle in the appropriate gear. The engine speed control then acted as a limiter to hold speed to the required value. This was beneficial, as manual speed control at the stability thresholds proved to be difficult to maintain because of vehicle cab vibration, high drag during an aggressive manoeuvre, and driver work load. The actual speeds used in the various tests were 34, 40, 47, 55, 63, 72, 77, 80, 84, 89 and 94 km/h. The nominal speeds used by the driver were in miles per hour

and differed somewhat from the actual values at the highest speed.

All tests except for the two right turns were conducted with outriggers and safety cables installed.

3.4.1/ Offtracking

The interaction of large trucks with highway geometrics was not specifically included in the study. It is, however, perhaps the most evident manifestation of increasing truck size to the motoring public in urban communities. Large trucks simply take more space and time to make turns than smaller trucks and, thus, appear to impede traffic. Three tests, therefore, were added to illustrate the space requirements needed for turns and to demonstrate the swept paths.

Steady-state offtracking is the most widely understood measure of the turning capability of large trucks. In normal driving, however, a steady-state offtracking situation would only likely be encountered in a 270° cloverleaf turn on a freeway ramp. In many cases these ramps are made up not of a principal circular arc with entry and exit spirals, but of several spirals and curves to accommodate the local space and terrain requirements. Trucks using these less regular ramps may not reach a true steady state. Nevertheless, steady-state offtracking remains a useful ranking of the space required to turn a large truck, though it may be somewhat misleading for some turns.

Steady-state offtracking was determined by driving the loaded vehicle on a high-friction surface at low speed, less than 5 km/h, in a circle of radius 29.87 m. The turn was made with the truck on the inside of the circle with the tractor outer front wheel following the circumference. The vehicle traversed the circle until steady-state offtracking had been achieved and continued to about one full revolution. Measurements were then taken from the centre of the circle to each axle's innermost tire. The test was repeated in the opposite direction to determine if axle or chassis misalignment affected the results. The test course is shown in Figure 13. This test was conducted at Blainville.

3.4.2/ Right-Hand Turn

The 90° right-hand turn is probably the most demanding turning manoeuvre for large trucks. In urban areas, or where there are low truck volumes, a small curve radius may be used. When a long truck comes to such an

intersection, where the truck is too large to make the turn with a simple steady steer input by the driver, there are two strategies available to create more space for the turn. Either the driver can move to the left of the entry lane to increase the radius, or he can move ahead and intrude into lanes beside the exit lane in the roadway into which the turn is being made. In either case, the driver is using the space of other vehicles, which increases the hazard of the turn. In the first case, it is possible that the driver of a small vehicle also intending to turn right could misunderstand the truck driver's intention in the initial move to the left and become trapped to the right of the truck as the vehicle started to turn to the right. This strategy is, therefore, considered undesirable. The second strategy also uses the space of other vehicles, but at least the presence and intention of the truck are clear throughout, and the truck driver would not normally enter that space if oncoming vehicles were too close.

Vehicle trajectory in a right-hand turn was evaluated using a 15 m curb radius, with entry and exit lane widths of 3.66 m, as shown in Figure 14. This has been used in highway geometric design standards for many years for turns from a two-lane two-way road into a four-lane two-way road, where the vehicle may exit in the left-hand lane rather than the right-hand lane. The drivers task is to approach the turn in the entry lane and make the "best" turn possible to exit ultimately in the right-hand exit lane. Definition of the "best" turn was left to the judgement of the driver, who repeated turns until satisfied that no further improvement could be made. The swept path of the tractor left front wheel, and rear trailer right rear wheel, were marked with traffic cones on the rays shown in Figure 14. When the "best" turn was achieved, the positions of the cones were measured, and hence, the turn swept path was recorded. This test was conducted at Centralia. The MTC International tractor was used as the power unit for all vehicles, and the trailers were empty.

3.4.3/ Channelized Right Turn

Vehicle trajectory in a channelized right-hand turn was evaluated using a 25 m curb radius with a channel width of 5.5 m. Entry and exit lane widths were 3.66 m, and deceleration and acceleration taper lengths were 75 and 50 m, respectively. The overall course, with island geometry, is shown in Figure 15. This is a typical highway geometric design standard for use in urban areas, where property presents a problem and speeds are low. The taper lengths assume entry and exit roadway speed limits of 60 km/h. The turn might be superelevated and would have an advisory

speed limit of 25 or 30 km/h.

This test was conducted at Centralia, with the MTC International used as the power unit for all vehicles and the test trailers empty.

This procedure results in measurement of the transient offtracking of the vehicle during passage through the channel, with the tractor following the most favourable line. In practice, there would be a gutter, perhaps 0.30 m (1 ft) wide on the left-hand side, which the driver would not normally use, and the turn might well be made at some speed when the lateral acceleration would tend to reduce the offtracking. Of course, in a congested traffic situation the turn could also be taken at a very low speed.

3.4.4/ Air Brake System

Balanced braking of a combination vehicle requires that the brake systems of all vehicle units be compatible so that pneumatic balance and torque balance can be achieved at each axle. In addition, short brake application and release times provide a brake system responsive to the driver's needs and reduce stopping distance and fuel consumption. Pneumatic balance and brake timing are both determined by the details for the air brake system, valves, and plumbing. Torque balance is determined by the foundation brake characteristics and axle loads and is a much more complex subject. A comprehensive treatment of the braking characteristics of combination vehicles was beyond the scope of the study. The issues of air brake system compatibility, however, are much more straightforward and could be illustrated by two tests.

1/ The first test follows the style of SAE Standard J982a for timing of the air brake system of a single vehicle unit. The test was, however, applied to the entire vehicle as an operational combination. The test uses a maximum rate brake application, with a regulated air supply at 689 kPa (100 psi), and the time for the air pressure at each axle to reach 413 kPa (60 psi) is determined. The pressures at each axle are also found. Pressure differentials can cause differences in torque between axles, affecting the overall brake balance. Brake release times, which affect the drag on combination vehicles, were also determined. This test is very aggressive, as the high airflow rate might, for instance, overcome "sticky" valves that would take a significant pressure differential to crack. This test represents the rare emergency brake situation where maximum performance is demanded.

2/ The second test was a service brake application, with treadle valve travel limited to provide about 118 kPa (20 psi) with a 689 kPa (100 psi) supply and a normal rate brake application. The timing and pressure differentials in this test illustrate how the air system behaves in normal use, the usual case.

This test was conducted at Centralia. The vehicle was stationary.

3.4.5/ Straight-Line Braking Demonstration

The action of braking an empty combination vehicle to a halt on a low-friction surface may result in loss of vehicle control if wheels are locked. The physical characteristics of current braking systems make it extremely difficult to conduct rigorous tests and obtain repeatable results that can be generalized to other vehicles. A series of straight-line stops was therefore conducted to demonstrate modes in which vehicles may become unstable.

In this demonstration the vehicle was driven onto the wet low-friction test area, which had an approximate skid number of 20 at 47 km/h, and braked to a halt. A series of runs was conducted with increasing brake application until all wheels of an axle group locked. The driver was allowed to steer as necessary to keep the tractor within the traffic lane. The speed was low enough that incipient unstable behaviour was always evident, but it was not so high as to be unnecessarily aggressive.

The primary results of this test were video tapes showing the vehicle's response to the braking input.

This test was conducted at Centralia.

3.4.6/ Evasive Manoeuvre

This test is representative of an obstacle avoidance manoeuvre on a two-lane, two-way highway, where the sudden appearance of an obstacle necessitates a fast lane change to the left, then return to the original lane to avoid oncoming traffic. The test course was laid out on a wet low-friction surface, using traffic cones as shown in Figure 16. The driver's task was to negotiate the course at constant speed and manoeuvre the empty vehicle through the gates, without loss of control or contact of any of the cones by the vehicle. A sequence of runs was conducted at

increasing speeds until the vehicle became unstable by tractor jackknife, trailer swing, or dolly jackknife, or trailer response resulted in an unacceptable slide out of lane, in excess of 1 m. Runs were repeated when responses were found to be inconsistent with the trend established by preceding runs, or when any cone was struck. When a run was made in which the vehicle response was unstable or undesirable, additional runs, varying by no more than 3 km/h, were conducted to bracket the stability boundary.

This test was conducted at Centralia. It was originally proposed as a lane-change manoeuvre, which is described in Section 3.4.8. However, this task proved too easy for the driver to negotiate for most vehicles when the critical gate size for the most demanding vehicle was used. In the experience of ministry staff, speeds in excess of 63 km/h were unduly hazardous for an empty vehicle equipped with safety cables on the wet low-friction surface. While the test area was provided with a high-friction shoulder, it was considered that the energy and momentum in total loss of control of a double or triple at any higher speed would be unnecessarily hazardous. Experience has shown that while the test driver is able to duplicate such manoeuvres consistently, the mode of loss of control may not be predictable, so speeds had to be limited for reasons of safety.

A symmetrical gate arrangement was selected for the evasive manoeuvre, and the gate size was selected as the minimum that could be negotiated by the most critical vehicle at a speed below the 63 km/h safety limit.

3.4.7/ Sinusoidal Steer

In this manoeuvre, the driver approached an open high-friction test area at constant speed with a loaded vehicle and executed a sinusoidal steer input at the steering wheel. This created a sinusoidal lateral acceleration input at the tractor, which resulted in a sidestep to the left, a vehicle trajectory similar to the single lane change described in Section 3.4.8. The lane change is constrained within a 3.66 m (12 ft) lane, whereas the sinusoidal steer results in a variable sidestep depending upon the speed and steer amplitude. The steer input was made to achieve a tractor lateral acceleration of about 0.15 g.

This steer input is simply a standard method by which lateral/directional response of the vehicle could be excited. The input was chosen to be large enough to get a reasonable response from the vehicle, but not so

large that units of the most responsive vehicles would be sliding or rolling excessively. This steer input permitted the lateral acceleration of each trailer of a combination vehicle to be examined, relative to the tractor lateral acceleration. These acceleration ratios, properly known as rearward amplification of lateral acceleration, are an important inherent dynamic characteristic of combination vehicles. An acceleration ratio no greater than unity means the trailer has a lower acceleration than the tractor, so basically the driver may be considered in control of vehicle response as he is in a position to sense the greatest acceleration in the vehicle. An acceleration ratio greater than unity means a trailer has a higher lateral acceleration than the tractor, and if the ratio and tractor lateral acceleration are high enough, the trailer may slide or roll over even though the driver feels the tractor is still fully under control.

A vehicle that has a higher rearward amplification than another has greater response per unit steer input. This means that it is more sensitive, or less stable, in its lateral/directional dynamic characteristics. This test, then, examines the inherent dynamic stability of the vehicle, an important property.

The test was run at speeds of 63, 84, and 94 km/h, which were the actual speeds in the gear that came closest to the target speeds of 60, 80, and 100 km/h. Steer periods of 4, 3.5, 3, 2.5, and 2 s were used. A true-tracking, sinusoidal input computer program for the Freightliner, using a 37.5:1 steer ratio, provided the necessary steer amplitudes to generate approximately 0.15 g lateral acceleration at the tractor for each speed and steer period tested. These amplitudes were provided to the driver by means of indicators on the steering wheel.

Since it was considered somewhat difficult for the driver to estimate and perform a steer input of specific period, an electronic device was developed that provided a guide. This steer period generator (SPG) permitted the driver to select the desired steer period by means of a switch, in increments of 0.5 s. Immediately after the gyro was uncaged, the driver would start the SPG and follow a light sequence given by a display box to achieve the correct steer period. This device worked well, as the driver was able to conduct the test in an orderly manner without the need for wasted runs to achieve a particular period by a series of trials.

This test was conducted at Blainville.

3.4.8/ Lane Change

The lane change on a standard highway requires a steer input by the driver that is similar to the sinusoidal steer. The amplitude of the steer input must be such that a sidestep of 3.66 m (12 ft) is achieved if the vehicle starts in the centre of one lane and moves over to the centre of an adjacent lane. This test is representative of an obstacle avoidance manoeuvre on a multilane highway, where the sudden appearance of an obstacle necessitates a fast lane change to the left.

The test course was laid out on a high-friction surface, as shown in Figure 17. The 30 m (98 ft) gate was selected so that speeds at the limits of stability for all vehicles would be in the range of 70 to 90 km/h. The vehicle was loaded, and the driver approached the course at constant speed. The driver's task was to manoeuvre the vehicle through the gates while maintaining speed, without loss of control or contact of any of the cones by the vehicle. A sequence of runs was conducted at increasing speeds until the vehicle became unstable by rollover or trailer swing, or trailer response resulted in an unacceptable swing out of lane, defined here as in excess of 1 m. The sinusoidal steer test described in Section 3.4.7 is a subcritical test, designed to display the dynamic characteristics of a vehicle. This test takes basically the same manoeuvre as the sinusoidal steer, to determine the limits of stability of the vehicle and demonstrate the mode by which it becomes unstable. The cone layout simply imposes a task on the driver and ensures repeatable results.

Runs were repeated when responses were found to be inconsistent with the trend established by preceding runs or when any cone was struck. When a run was made in which the response was unstable or undesirable, additional runs, varying by no more than 3 km/h, were conducted to bracket the stability boundary. The test was terminated if the vehicle reached 100 km/h, a typical maximum legal speed in provinces of Canada, and was still able to make the manoeuvre successfully.

This test was conducted at Blainville.

3.4.9/ Normal Straight-Line Driving

The trailers of combination vehicles tend to sway a small amount in straight-line driving due to road roughness and normal small steer corrections by the driver. This sway is related to vehicle configuration in

the same way as rearward amplification of lateral acceleration. Some jurisdictions may impose a 75 mm (3 in) sway amplitude limit on trailers. The limit, however, is non-specific because it is not related to the input to the vehicle. It is also difficult, if not impossible, to enforce because the sway cannot be measured; it can only be subjectively estimated.

This test was conducted at Blainville.

3.4.10/ Steady Circular Turn

A loaded vehicle can roll over in a steady turn if its speed is high enough. Such a situation typically occurs for vehicles with a high centre of gravity when driven at excessive speed on a freeway ramp. There is often dynamics involved in such accidents, due to braking, steering, or both, as the driver attempts to negotiate the ramp. However, the essential mechanism involved is that of rollover in a steady turn, which is an important inherent stability characteristic of a vehicle. This test examined that characteristic.

Static rollover characteristics of all vehicles tested, except the triples, were examined in a parallel part of the study conducted by Centre de Recherche Industrielle du Quebec (CRIQ), using a tilt table built for this purpose. Vehicles were provided to CRIQ staff, loaded as for these tests, except that outrigger outer sections were removed to get the vehicle onto the tilt table. The vehicle was driven onto the table, with load cells located strategically beneath wheel groups on each side of the vehicle. Axles and the vehicle body were suitably restrained, and tilt meters were attached. The table was then continuously tilted until enough axles on the high side of the vehicle had lifted for the vehicle to be deemed to have reached the rollover point. Results of the tilt tests have been presented separately by CRIQ [12]. The tilt test provides static roll characteristics of a vehicle. It may be presumed these would be related to the rollover characteristics arising from a steady run.

The steady circular turn course was laid out using traffic cones on a dry high-friction surface, as shown in Figure 18. The circle had a radius of 50 m (164 ft) and was approached along a tangent leading to a 100 m (328 ft) long spiral. The vehicle was loaded and the driver followed the approach at a specified constant speed, entered the circular turn as smoothly as possible, and followed on the outside for 90 to 180°, or as

long as possible. A sequence of runs was conducted at increasing speeds until the vehicle became unstable by rollover or trailer swing, or the driver could not maintain either the desired trajectory or the speed. Sufficient runs were made to map out the vehicle roll response as a function of speed.

The outriggers were set such that the vehicle wheels on the inside of the turn would lift by 0.15 to 0.20 m (0.5 to 0.65 ft) at outrigger touchdown, which corresponds to about 6 to 7° of body roll. The outrigger clearance settings varied somewhat between vehicle units and vehicles, because of attachment and adjustment limitations. More important, however, were the differences in suspension stiffness and longitudinal stiffness between vehicles. The A-trains could clearly roll over the rear trailer, whereas for the others, outrigger touchdown might have occurred, but the entire vehicle could still be somewhat short of the point of rollover. Outrigger touchdown, therefore, simply denoted a point beyond which further testing was impractical. There would not necessarily be any relationship between these points for each vehicle. It was, therefore, considered more useful to map the vehicle characteristics as a function of speed rather than simply establishing an arbitrary outrigger touchdown point.

This test was conducted within the vehicle dynamics area at Blainville.

3.5/ Data Capture

The data acquisition system consisted of multiplex systems mounted in the sleeper portion of the MTC Freightliner and instrumentation boxes on the trailers. Electrical signals produced by the transducers were conditioned by individual plug-in-type adapter cards within the multiplex unit. The conditioned output signals were transmitted from each multiplex system to a control unit in the tractor, where they were digitized at a rate of 100 samples/s for each channel and transformed into a pulse-code modulated (PCM) data stream in a standard IRIG format. The PCM data stream was broadcast by radio telemetry from the tractor to a ground station, using a radio frequency licensed to the ministry for use at both Centralia and Blainville.

The ground station was located in the MTC building at Centralia. All of the essential elements of ground station equipment were installed in a former transit bus, which served as the ground station during tests at Blainville.

The ground station received the PCM data stream and recorded it in analog form on an instrumentation tape recorder. IRIG B time code was recorded on a second track of the recorder so that the location of a particular run could be found easily if data playback was required. This recording was for archival and backup purposes.

The PCM data stream was processed by a decommutator, which formatted it into a bit parallel, word serial, input stream for an Hewlett-Packard HP-1000 A700 computer in the ground station. The computer read each run in real time and created a raw data file on disk for subsequent processing. The project engineer at the computer graphics terminal had a quick-look display that provided an overview of system status functioning and data quality while the run was in progress. The raw data were reviewed by the project engineer on a graphics display, to determine whether all critical data channels were functioning correctly and whether the run appeared to meet the specified test conditions. The raw data file was then read, electronic calibrations were applied, each channel was converted to engineering units, and a calibrated data file was created. Quantities of interest were derived, and those critical to the test were displayed to the project engineer, who used them to make recommendations for the next run by radio to the test director on the track.

Before each test session, an electronic calibration of the entire data acquisition system was conducted. Any adjustments were identified and made, and a second calibration was recorded. Before each test run, the control unit on the tractor was made to step automatically through a calibration sequence. This was recorded as part of the run data, to permit current system calibrations to be used for each run.

Each run was recorded on colour video tape, from the vantage point of a cherry picker parked just before the initiation of the manoeuvre, from other vantage points of interest, or both. Each run was preceded by a shot of the day and run numbers, so that it was positively identifiable. The audio track of the video system was used to record ambient noise during testing, including incidental radio transmissions.

Still colour photographs and colour slides of the vehicles, equipment, and activities were also taken. Manual notes and logs of all test conditions and observations were made. A log of all test runs was maintained within the computer.

A detailed description of data capture is presented elsewhere [3].

3.6/ Data Processing

At the beginning of each day, certain data files and procedures were initialized within the HP-1000 computer system. Data from each run were captured in real time by the HP-1000 and processed concurrent with testing, as described previously. After each test session, all raw data files; other files created in support of the data processing process, such as the run log file and a summary file of derived quantities; and all data input files which controlled the data processing were archived to a tape. The archived tape was indexed and complete, so that the processing of any particular run could be reconstructed.

Upon completion of the test program, all data processing procedures and supporting data files were exhaustively reviewed, and necessary enhancements were implemented and validated. Every run was also carefully reviewed, and those runs that did not meet the particular test objective, or were otherwise so flawed that the data could not be processed, were discarded.

Data processing proceeded in four phases:
1/ raw data correction
2/ calibration
3/ treatment
4/ extraction of results

The first phase, raw data correction, simply corrected any data frames in which telemetry dropout occurred. This resulted in partial loss of the frame during which dropout occurred, total loss of an unknown number of complete frames, and capture of one or two scrambled frames while the computer data acquisition was regaining synchronization with the decommutator. Runs were rejected in which there occurred frequent dropouts or dropouts during the steer input or vehicle response.

Calibration proceeded in two phases. As previously mentioned, the onboard data acquisition system was commanded through an electronic calibration sequence at the beginning of data acquisition for each run. The calibration sequence consisted of approximately 0.5 s of each of negative full scale, zero, and positive full scale. This calibration was used on every run to modify the value used for conversion to engineering units, the second phase of calibration.

The term "treatment" is used for the sequence of operations whereby the now calibrated data were processed so that specific quantities of interest for a particular test could be derived. Some of these operations were applied to the output of a particular instrument, while others were used rather generally on various types of data. The following treatments were used in data processing:

1/ transformation of speeds of all free-rolling wheels to the speed of the tractor right front wheel;
2/ transformation of the sawtooth wave distance measurement to actual distance;
3/ correction of trailer lateral accelerations for the gravitational effect of roll angle;
4/ integration of yaw and roll rates to yaw and roll angles, respectively;
5/ detrending of data to remove zero offsets and drift; and
6/ filtering of data to remove unwanted frequency content.

The final phase of data processing was extraction of results. The method used depended entirely on the test being processed. Details of the methods are presented elsewhere [3].

4/ PERFORMANCE MEASURES

The various vehicle configurations are evaluated across the entire study, using various performance measures. Some of these performance measures are addressed by simulation or analysis of various kinds, others by test, and some by both.

The following performance measures provide the basis of what will be considered from tests:

1/ steady-state roll characteristics, derived from circular turn manoeuvres for loaded vehicles;
2/ dynamic roll threshold, derived from lane-change manoeuvres for loaded vehicles;
3/ roll mode characteristics, from the manoeuvres of 1 and 2;
4/ rearward amplification of lateral acceleration, from sinusoidal steer and lane-change manoeuvres;
5/ yaw/directional stability (jackknife and trailer swing), derived from evasive manoeuvres with an empty vehicle on a low-friction surface;
6/ straight-line trailer sway for loaded vehicles;
7/ vehicle stability characteristics in straight-line emergency braking, empty on a low-friction surface;
8/ high-speed offtracking, derived from the steady circular turn;
9/ lateral loads at the tractor fifth wheel, derived from the steady circular turn, lane-change manoeuvres, and the sinusoidal steer input;
10/ yaw response gains and lag times;
11/ vehicle speed at lateral/directional and rollover stability thresholds;
12/ steady-state offtracking;
13/ swept paths in typical right-hand turns;
14/ air brake system application, release timing, and pneumatic balance.

These performance measures were computed from the measured data by the HP-1000 computer, as described previously. The values were stored in a file indexed by run, making it possible to display vehicle response characteristics against input parameters, for purposes of test management and data analysis.

5/ RESULTS

5.1/ Offtracking

Steady-state offtracking is considered an indicator of vehicle turning ability. Offtracking of the vehicle was evaluated by making a complete turn around a circle of radius 29.87 m (98 ft). The vehicle outer wheel tracked the inside of the circle. Turns were made in both directions. At the end of a turn, the vehicle was parked and the radius to each axle was measured, according to the standard test procedure [3]. A typical situation is shown in Figure 19.

The results are shown in Table 7. The 45 ft (13.72 m) semi has large offtracking because of the length of the trailer and the rear placement of the bogie. The three doubles all have much less offtracking because of their short trailers and additional articulation points. The B-train has greatest offtracking of the three because of the rearward location of the turn centre of its lead trailer. The C-train has slightly less offtracking than the comparable A-train, as found previously [11], and the same result pertains for the two triples. The differences within the three doubles, and the two triples, which are attributable to the method of hitching, are not regarded as of great practical significance in their turning requirements.

The measured data for all vehicles were compared to data generated by a simple offtracking formula [13]. The difference between actual and computed values was always less than 0.5% for all axles, which is so small that steady-state offtracking can clearly be estimated very accurately by this simple formula.

Table 7/ Offtracking at Rear Axle

Vehicle	Offtracking (m)
45 ft semi	2.65
A-double	1.45
B-double	1.69
C-double	1.35
A-triple	2.77
C-triple	2.52

5.2/ Right-Hand Turn

A right-hand turn at an intersection is a demanding manoeuvre for a large truck. The vehicle's swept path was measured according to the standard test procedure [3], in a 90° right-hand turn of 15 m (49.2 ft) radius. This radius is typical in an urban area or in areas of limited truck traffic. The driver was asked to make the best turn possible, without moving to the left out of the entry lane, and ending ultimately in the curb lane of the exit roadway. The driver manoeuvred the tractor to make the turn with the inner wheels of the last axle of the vehicle tracking closely around the curb. This required the driver to pull forward into available space beside the exit lane to create room for the turn. The driver then made a complex steer input to accomplish the turn. A typical vehicle is shown in Figure 20 during the turn.

The maximum excursion out of lane and the length of that excursion are presented in Table 8. The doubles barely intruded into the lane adjacent to the exit lane, whereas the semi required more than half of it, and the triples required all that lane and a little more. While this turn is very different than offtracking, the ranking of vehicles is the same for both. This test was conducted at a creep speed and represents about the best possible turn. A rolling turn would probably result in a greater excursion out of the exit lane.

Table 8/ Right-Hand Turn

Vehicle	Maximum Excursion Out of Lane (m)	Length of Excursion (m)
45-ft semi	2.20	19.20
A-double	0.40	7.50
B-double	0.90	18.00
C-double	0.80	8.40
A-triple	3.80	19.40
C-triple	3.70	22.00

5.3/ Channelized Right Turn

The vehicle's swept path in a channelized right turn was measured according to the standard test procedure [1]. The roadway geometry used for this test is typical of an urban area, where space is limited. The curb radius was 25 m (82 ft), and entry and exit tapers typical of four-lane roadways with a 60 km/h speed limit were used. Such roadway geometrics may restrict access of the largest vehicles.

A typical vehicle is shown during the turn in Figure 21. The minimum clearance of the innermost wheel of the rear trailer's rear axle from the inner curb is shown in Table 9. The doubles made it easily through the channel, while the semi had less space, and the triples barely made it. Remember that the tractor left front wheel was tracking the curb. A driver would normally leave some clearance on this side, so the triples would be very close to running over the inside curb.

The test was run at creep speed, the worst condition, as the effect of lateral acceleration is to reduce the geometric offtracking measured in this test. However, this roadway geometry is used at busy intersections where traffic may not always be free-flowing, so the test may be considered realistic.

Table 9/ Channelized Right Turn

Vehicle	Curb Clearance (m)
45-ft semi	0.89
A-double	1.85
B-double	1.55
C-double	1.66
A-triple	0.51
C-triple	0.18

5.4/ Air Brake System

The air brake system of the combination was evaluated according to the standard test procedure [1].

The trailer air brake system was inspected. All slack adjusters were adjusted to the minimum, about 32 mm (1.25 in) stroke on each axle. The tractor was supplied with shop air, regulated at 689 kPa (100 psi). Pressure transducers were installed at all trailer and dolly axles.

The SAE J982a style test was performed on the A- and C-train triples for the tractor-trailer when air to the first dolly was shut off; for the double, which resulted when air to the second dolly was shut off; and for the full triple combination. The results of these tests are presented in Tables 10, 11, and 12. The results are the average of several tests in each case, with a time resolution of 0.02 s. A typical time history response of application and release for each triple is presented in

Figure 22 -- the A-train is the solid line and the C-train is the broken line.

Table 10/ Air Brake Timing, Semi of Triples

Location	Application Timing 0-60 psi (s) A-Train	C-Train	Release Timing to 5 psi (s) A-Train	C-Train
Treadle	0.02	0.05	0.18	0.14
Axle 2	0.36	0.37	0.58	0.57
Axle 4	0.37	0.37	0.78	0.75

Table 11/ Air Brake Timing, Double of Triples

Location	Application Timing 0-60 psi (s) A-Train	C-Train	Release Timing to 5 psi (s) A-Train	C-Train
Treadle	0.03	0.08	0.17	0.16
Axle 2	0.37	0.38	0.57	0.56
Axle 4	0.55	0.76	1.41	2.06
Axle 5	0.59	0.96	1.47	2.19
Axle 6	0.67	0.85	1.51	2.12

Table 12/ Air Brake Timing, Triples

Location	Application Timing 0-60 psi (s) A-Train	C-Train	Release Timing to 5 psi (s) A-Train	C-Train
Treadle	0.07	0.11	0.18	0.16
Axle 2	0.37	0.39	0.58	0.56
Axle 4	0.54	0.96	1.42	3.68
Axle 5	0.57	1.25	1.50	3.78
Axle 6	0.85	1.52	1.92	3.98
Axle 7	0.95	1.70	1.95	4.00
Axle 8	0.97	1.57	2.05	4.08

Two interest comparisons arise from these three tables. First, examine

the effect of adding trailers progressively for the A-train. As a semi (Table 10), application times for tractor and trailer were both 0.37 s, an ideal situation. When the second trailer was added (Table 11), the first trailer application time was prolonged to 0.55 s. When the rear trailer was added (Table 12), the second trailer application time was increased from 0.67 to 0.85 s. As each trailer was added, only the preceding trailer was affected, as the plumbing and valves prevented feedback more than one trailer ahead. Similar results pertain for the release times.

The A-train dollies both had booster relay valves to speed the signal to the following trailers. The C-train was not so equipped. Table 10 shows that application times for the A- and C-trains are the same within test errors, as these were, in fact, the same combination tested at different times. When additional trailers were added, however, the benefits of the booster relay valve becomes apparent. Brake application time for the C-train double is 0.85 s, 27% longer than for the A-train, and it is 1.57 s for the C-train triple, 62% longer than for the A-train. Not only does the booster relay valve speed both application and release times, it inhibits the third trailer, slowing the first, as happens for the C-train. Figure 22 shows that the C-train application pressure was slightly less than for the A-train. If it had been higher, the C-train application times would have been longer.

Notice in Table 12 for both vehicles that axle 5 on the first dolly is faster than axle 6 on the second trailer. This means that as the brakes are applied and the vehicle starts to slow, the inertia of the last two trailers bears momentarily on the first dolly as it starts to brake but before the brakes on the last two trailers become effective. In an aggressive braking situation with an empty vehicle on a low-friction surface, this provides potential for a dolly jackknife. However, the timing of the corresponding axles 7 and 8 on the rear trailer are very close for the A-train and are even reversed for the C-train, with the dolly axle reaching full braking after the trailer axle. This latter situation is considered desirable if it can be achieved without an excessive brake application time, which was certainly not the case with the C-train. This vehicle was created from available vehicle units, the three trailers, and the two B-dollies. It was not designed as a combination as was the A-train. The desirable rear trailer brake timing was a result simply of hasty assembly of the second B-dolly from less than ideal parts. Note that while recent work has shown that a big difference in timing between a tractor and trailer has little practical effect on

the tendency to jackknife [14], no such work is known for dolly jackknife on doubles or triples.

The application times are comparable with those obtained from tests conducted previously by MTC on other triples combinations [15,16]. The release times are considered long, however, especially as it was shown that a quick-release valve operating with a booster relay valve could halve the release time [16]. Not only can a faster or more responsive braking system be created at little, if any, cost difference to an "ordinary" system, but if a fast release can also be obtained, then a modest amount of fuel can be saved by reducing the need to accelerate against momentarily dragging brakes. Indeed, an elementary calculation can show than a quick-release valve can pay for itself through fuel saving in a fraction of the life of the trailer.

The application and release timing for the other four vehicles is summarized in Tables 13 and 14. These results are typical of other tests on similar combinations [14,16]. As noted previously, the timings for the doubles would all have been improved if each combination had used a booster relay valve. The B-train was faster than the A- or C-train, first because it lacked a converter dolly so the plumbing was cleaner, and second because it was equipped with an anti-lock braking system which requires faster components. The release times of the A- and C-train doubles are both considered excessive.

Table 13/ Air Brake Application Timing Summary, 0-60 psi (s)

Location	45 ft Semi	A-Double	B-Double	C-Double
Treadle	0.07	0.04	0.04	0.03
Axle 2	0.41	0.39	0.40	0.43
Axle 4	0.49	0.57	0.56	0.54
Axle 5	0.45	0.56	0.62	0.53
Axle 6	-	0.81	-	0.85
Axle 7	-	0.79	-	0.83
Axle 8	-	0.77	0.68	0.83

Table 14/ Air Brake Release Timing Summary, to 5 psi (s)

Location	45 ft Semi	A-Double	B-Double	C-Double
Treadle	0.19	0.19	0.12	0.18
Axle 2	0.64	0.65	0.54	0.64
Axle 4	0.94	3.02	1.46	1.65
Axle 5	0.88	3.04	1.50	1.59
Axle 6	-	2.26	-	1.96
Axle 7	-	2.31	-	2.39
Axle 8	-	2.28	1.56	2.43

The greatest pressure differential between axles of a vehicle just before brake release ranged between 21 and 48 kPa (3 and 7 psi); the differential for most axles was not more than 21 kPa (3 psi). No clear patterns emerged from this.

A service brake application test was also conducted, where treadle valve travel was limited to keep the final pressure to about 138 kPa (20 psi). In general, application times were similar to those previously reported, because the brake application was not nearly so rapid. Release times were faster, as would be expected, and for most, there were no significant pressure differentials between axles.

This test has illustrated that the air brake system performance depends upon the number of vehicle units -- trailer and dollies. It has also shown that performance depends upon the selection and installation of components. Fast application and release times provide the driver with a responsive brake system. Proper pneumatic balance -- low pressure differentials between axles -- is part of obtaining proper distribution of braking to all axles of the combination.

5.5/ Straight-Line Braking

It is difficult to conduct rigorous braking tests and achieve consistent results. A demonstration of modes of instability of the combination vehicle in straight-line braking was, therefore, conducted. A series of runs was made where the empty vehicle approached the low-friction test area at 47 km/h and the driver braked using the treadle valve, with a regulated application pressure. Application pressure was increased on each run, to the point where groups of wheels locked. The driver was instructed not to attempt to counter any loss of control, except as necessary to avoid hazard. The standard test procedure was followed [1].

The vehicle combination was evaluated primarily in terms of the yaw response of vehicle units, which is the heading angle of the vehicle unit (in degrees), with zero parallel to the original direction of travel. Any significant yaw seen in this manoeuvre arose from lateral/directional instability of a vehicle unit.

The vehicles all remained fully under control when application pressure was insufficient to lock all braked axles. The results of the last run for each vehicle are presented in Table 15. In most cases, the limiting friction of the surface, a deceleration of about 0.15 g, was reached at a brake application pressure of 159 to 173 kPa (23 to 25 psi). At this pressure, most of the braked wheels were locking. The A-train double and the two triples became unstable at pressures little more than this, whereas the 45 ft (13.72 m) semi and the B- and C-train doubles required considerably harder braking before they became unstable.

Table 15/ Instability in Straight-Line Braking

Vehicle	Brake Pressure (psi)	Mode of Instability
45 ft Semi	50	Tractor jackknife
A-Double	32	Dolly jackknife
B-Double	41	Tractor jackknife
C-Double	45	Tractor jackknife
A-Triple	30	Tractor jackknife, driver recovered
C-Triple	34	Tractor jackknife, driver recovered

The tractor of the 45 ft (13.72 m) semi jackknifed to the right, as illustrated in Figure 23 and shown in Figure 25 in its final stopped condition. The dolly of the A-train double jackknifed to the right, as shown in Figure 24. While the whole vehicle remained within the lane during this stop, the dolly actually was unstable. The combination of speed, brake application pressure, and surface friction was such that the instability was demonstrated quite gently. If either speed or brake application pressure had been greater, or the friction had been lower, the dolly jackknife could have been much more violent. The dolly would have rotated until it struck the rear of the lead trailer, and presuming the hitch did not fail, the trailer would then have swung around. The test condition was selected so that the mode of instability was demonstrated but that this violent and hazardous consequence was avoided. The B- and C-train doubles and the triples all experienced tractor jackknife.

In the case of both triples, the driver released the brakes, steered to recover control of the tractor, and drove out of the manoeuvre without coming to a full stop. The tractor jackknifes were predominantly to the left, the direction of the crossfall on the test area. However, some were to the right, possibly due to the local surface characteristics and steer.

The demonstration was conducted without front axle brakes on the tractor. When a braked wheel locks, it has very little sideforce capability. However, if all wheels except those at the steer axle lock, the steer axle can still develop the substantial sideforces that are required to manoeuvre the vehicle in normal driving. Further, as the front axle is steered, a drag is created, and the inertia of the trailer or trailers is enough to overcome the limited sideforce capability of the locked tractor drive axles and push the rear of the tractor sideways, as shown in Figure 23. If front axle brakes had been used, the sideforce capability of the locked front wheels would have been very low, and the likelihood of tractor jackknife would have been greatly reduced if the driver kept them straight. The vehicle would simply slide to a stop, not necessarily entirely under control of the driver, but at least straight and possibly within the lane. Of course, with the addition of the front axle brakes, the inertial effect of towed units is increased, and there remains the possibility of trailer swing on B- or C-train combinations or dolly jackknife as seen in the A-train double.

5.6/ Evasive Manoeuvre

The object of this test was to evaluate empty vehicle lateral/directional characteristics at the limits of stability on a low-friction surface. A series of runs was made where the driver made an evasive manoeuvre, which is considered representative of a high-speed accident avoidance situation on a two-lane, two-way highway. The runs were made in accordance with the standard test procedure [1]. For most vehicles, the test used gates of 22.5 m (73.8 ft) for the lane change to the left and the return to the original lane, separated by 20 m (65.6 ft) in the left lane. However, the B-train double used gates of 20 m (65.6 ft), and the C-train triple used gates of 25 m (82 ft), as shown in Table 16. A typical test run for the B-train double is illustrated in Figure 26.

Table 16/ Instability in the Evasive Manoeuvre

Vehicle	Gate (m)	Limit Speed (km/h)	Mode of Instability
45 ft Semi	22.5	63	Reached limit of tractor control
A-Double	22.5	63	None
B-Double	20.0	54	Rear trailer swing
C-Double	22.5	63	Tractor pushed through return to original lane
A-Triple	22.5	58	Dolly jackknife and rear trailer swing
C-Triple	25.0	63	Tractor pushed through return to original lane, and rear trailer swing

The vehicles were evaluated primarily in terms of the yaw responses of their units.

The evasive manoeuvre is complex and subtle. The form of the steer input depends upon the layout of the course, the speed, and the handling characteristics of the vehicle. At a very low speed the steer input consists of two distinct sinusoidal steer inputs of opposite sign, the first for the lane change to the left and the second for the return to the original lane. As speed is increased, the two sine curves merge into a complex wave form, because the time in the left-hand lane is now insufficient for the driver to straighten out the tractor, so it follows a continuous curved path. As speed is increased further, the second half-wave of the first sinusoidal steer and the first half-wave of the second sinusoidal steer merge completely and the manoeuvre is accomplished in three continuous sinusoidal half-waves. As speed is increased even further the amplitude of the second of the three half-waves must be reduced. Unlike some other manoeuvres, the evasive manoeuvre can actually get easier for the driver as speed is increased, because the number of steering wheel movements decreases from five to three. It is actually easiest when the two distinct sinusoidal steers have merged into three continuous half-waves, each of the same period, as this steer input can be done in one smooth flowing motion. Beyond this point, the steer input gets more difficult as the amplitude of the half-waves changes. The frequency content of the steer input, therefore, changes with speed, and is more complex than the basically sinusoidal steer required by the lane change, discussed in Section 5.8. Because of the complexity of the manoeuvre, it is a little difficult to get consistent results, especially since each

vehicle has different frequency response characteristics and the frequency content of the input varies. For instance, a small steer error at a lower speed may result in an apparent unstable condition when, in fact, the driver might be able to make the manoeuvre rather easily at a somewhat higher speed, where the steer input can be made more smoothly.

In summary, therefore, the speed at which this manoeuvre can be made may be a little misleading as a ranking of the stability characteristics of the vehicle. Rather, attention should be given to the mode of instability, summarized in Table 16. The 45 ft (13.72 m) semi was clearly the most stable. It remained stable to the limit speed of 63 km/h, but at that speed with the best radius that the driver could achieve the trailer was just too long to go through the gate to return to the original lane. With both the A-train double and A-train triple the driver had excellent control of the tractor in this manoeuvre, as the short trailer exerts little force on the tractor. The A-train double just made the manoeuvre at 63 km/h, but the dolly was sliding through the gate to return to the original lane and was on the verge of a dolly jackknife, which would have resulted in rear trailer swing and total loss of control. In contrast, there was greater lateral acceleration at the rear trailer of the A-train triple, due to rearward amplification, as discussed in Section 5.3.7, and the second dolly jackknifed in the return to the original lane, and indeed, the rear trailer swung out of lane to the right. The B-train double experienced trailer swing at only 54 km/h, but it performed the manoeuvre with a gate of only 20 m (65.6 ft). The tractor of the C-train double was pushed through the original lane as it returned through the second gate. The tractor was at the limits of control, but the trailers remained stable. It is likely that the mode of instability would have been tractor jackknife, as occurred in a previous test of a C-train in such a manoeuvre [11]. The tractor of the C-train triple was also pushed through the original lane as it returned through the second gate, and there was also trailer swing. There was insufficient lateral traction to cause steering of any B-dolly in this manoeuvre.

5.7/ Sinusoidal Steer

The objective of this test was to evaluate characteristics of rearward amplification of lateral acceleration for each combination. A series of runs was made where the driver made a sinusoidal steer input to the vehicle while travelling at a steady speed, in accordance with the standard test procedure [1]. This test was conducted at speeds of 63, 84, and 94 km/h, with steer input periods between about 2 and 5 s.

The vehicle combination was evaluated in terms of the lateral acceleration responses of the vehicle units. The maximum lateral acceleration gain of each vehicle is presented in Table 17 for the three test speeds. Each gain is defined as the peak-to-peak trailer lateral acceleration response divided by the peak-to-peak tractor lateral acceleration, and is dimensionless [3]. The maximum value was estimated by scribing a line by French curve through the gains obtained from runs at the various steer periods at each speed. This procedure was not exact, but is clearly adequate to illustrate the major differences between vehicles.

Table 17/ Rearward Amplification of Lateral Acceleration at the Last Trailer

Vehicle	63 km/h	84 km/h	94 km/h
45 ft Semi	0.85	1.00	1.05
A-Double	1.10	--	1.85
B-Double	1.05	1.30	1.80
C-Double	--	1.30	1.50
A-Triple	1.50	2.60	3.30
C-Triple	1.15	1.30	1.70

It is clearly evident from Table 17 that rearward amplification increases with speed. It also increases rearward by trailer and is somewhat sensitive to steer period, as seen in Figure 27 for the A-train triple. The results, as seen in Figure 27 and Table 17, show that at highway speed, the A-train triple is a very responsive vehicle. The reason for this is that its inherent stability is rather low. Stability and response of mechanical systems have an inverse relationship. High stability means low response to input and vice versa. Figure 28 shows the rear trailer response of a typical run for a steer period of about 2.5 s at each test speed. At 63 km/h the response is nearly deadbeat; at 84 km/h the rear trailer is clearly oscillating; and at 94 km/h the rear trailer is oscillating strongly. These three time histories clearly depict the reduction in damping of the vehicle's lateral/directional response as speed is increased. Figure 29 shows the three comparable conditions for the C-train triple.

The responsiveness of the A-train triple made this and other tests difficult to conduct for this vehicle:

1/ On approach, small steer corrections made by the driver were amplified rearward so that a desired steady period before the manoeuvre was

rarely achieved. This made data detrending difficult [3] and may account for a certain amount of scatter in the data.

2/ The response to the manoeuvre itself continued to the point where the driver had to exit the test area; a complete response could not be obtained because the test area was simply not large enough.

3/ The steer inputs were very small, typically 25 to 35° of steering wheel angle, which is less than 1° steer at the front axle. This small steer resulted in a tractor lateral acceleration of about 0.1 to 0.15 g.

A rearward amplification of 3.0 did, on occasion, result in substantial trailer roll and sometimes trailer swing, even on the high-friction surface. However, tempering the steer input to avoid excessive rear trailer response resulted in such a small steer input that while it was closely sinusoidal at the steering wheel, it was often rather poorly balanced at the front axle. Responses, therefore, were often not well balanced, which means that the steer input contained, perhaps, substantial other periodic content besides the intended steer period.

It is for this reason that the rearward amplifications were computed as the ratio of peak-to-peak trailer lateral acceleration response to peak-to-peak tractor lateral acceleration. This significantly reduced the scatter in the results and avoided the issue of whether the first, second, or highest input and response peaks should be used as the basis for these ratios. Nevertheless, because the input was often unbalanced and not a pure sine wave, it was likely that the response was somewhat attenuated compared to what would result from a pure sine wave. The data presented in Table 17 are, therefore, considered optimistic, in the sense that they are probably lower than would arise from a perfect steering system or a computer simulation of the vehicle using a pure sine wave steer input.

Tests were only conducted to 94 km/h. It was apparent that the stability of the A-train triple was decreasing with increase in speed. This vehicle would be even less stable at a typical highway speed limit of 100 km/h. Actual speeds are often higher than this limit, and the vehicle would become yet less stable if actual speeds did exceed 100 km/h. These data are considered a powerful argument in favour of the comparable C-train configuration. A less effective alternative would be a restriction of A-train triples to a maximum speed of 80 km/h.

The results presented in Table 17 are reasonably consistent with other

test and simulation findings [17], though those results were obtained for somewhat different vehicles and loadings.

5.8/ Lane Change

The objective of this test was to evaluate vehicle stability characteristics in a dynamic manoeuvre. A series of runs was made where the driver made a lane-change manoeuvre, which is considered representative of a high-speed accident avoidance situation on a four-lane or divided highway. The runs were made in accordance with the standard test procedure [1].

The test used a gate of 30 m (98.4 ft) for the lane change. This was used to provide a vehicle speed of about 80 km/h, which is a typical speed limit and might permit some comparison of the results of this test with those described in the preceding sections.

The limit speed at which each vehicle became unstable in this manoeuvre, and the mode of instability, are presented in Table 18.

Table 18/ Instability in the Lane-Change Manoeuvre

Vehicle	Limit Speed (km/h)	Mode of Instability
45 ft Semi	95	None
A-Double	83	Rear trailer rollover
B-Double	88	Violent rear trailer swing and outrigger touchdown
C-Double	95	Lead trailer slide
A-Triple	74	Rear trailer swing
C-Triple	89	Second trailer slide and rear trailer swing

The 45 ft (13.72 m) semi was able to negotiate the course at the maximum test speed of 95 km/h and was, clearly, the most stable vehicle.

While this test was not conducted for the A-train double, the same test was conducted for a very similar vehicle in a previous test program, which resulted in slide and violent rollover of the rear trailer [11]. The rear trailer of the B-train double swung rather violently, and its outrigger touched down on both sides (Figure 30). The vehicle would not have rolled over, but the response was certainly undesirable. When the

C-train double reached a sufficiently high speed in the manoeuvre, the B-dolly steered out. This transferred lateral load from the rear trailer to the lead trailer tandem axles. These became overloaded, so the lead trailer slid left towards the edge of the lane, and the rear trailer simply tracked behind. The response of this vehicle was rather mild, certainly not as violent as that of the B-train double.

The A-train triple had such a high rearward amplification that at only 74 km/h the second dolly slid and the rear trailer swung violently out of lane, as shown in Figure 31. No outrigger touchdown occurred. Three considerations all provide a tendency to trailer swing rather than roll-over.

1/ The centre of gravity was low because of the method of loading and the underslung outriggers. Typical similar trailers in operation would have a considerably higher centre of gravity.
2/ The wheel track width was 2.59 m (102 in), whereas for the 45 ft (13.72 m) semi and all three doubles, it was 2.44 m (96 in).
3/ The sideforce capability of a single axle in such a manoeuvre is probably somewhat less than for a tandem axle.

Nevertheless, if the trailer centre of gravity had been at a more typical height, the rear trailer would undoubtedly have rolled over violently, as it did for the A-train double. While rollover was the "expected" mode of instability in such manoeuvres for this vehicle, this test shows that another mode of instability is possible. The C-train triple was relatively mild in its response compared to the A-train. The mechanism was the same as described earlier for the C-train double, except that both B-dollies steered out, and because of the extra trailer, the vehicle reached the edge of lane at only 72 km/h. However, the response was not violent, and testing continued until 89 km/h, when as a consequence of the second trailer slide, the rear trailer swung rather violently out of lane.

The sinusoidal steer test ranked the six vehicles in terms of stability: the higher the rearward amplification, the lower the stability. When the rearward amplifications of Table 17 are compared with the limit speeds of Table 18, it is seen that there is an inverse relationship between the speed at which this manoeuvre could be conducted and the rearward amplification. Rearward amplification, therefore, can be directly related to the likelihood of loss of control in a fast steer input such as might be made in an accident avoidance situation.

5.9/ Normal Straight-Line Driving

The objective of this test was to attempt to evaluate lateral motion of the rear trailer of the combination, the phenomenon known as trailer sway. A series of runs was made with the loaded vehicle driven normally at 94 km/h in a straight line, according to the standard test procedure [1].

Trailer sway is simply a low-level vehicle response. Sway amplitude is related to vehicle configuration and speed in the same way as the rearward amplification of lateral acceleration.

The slight steer corrections made in the course of normal driving, and roughness of the test track surface, resulted in rear trailer sway that was evaluated by root mean square (RMS) lateral acceleration of the rear trailer and RMS sway of the rear of the rear trailer relative to the tractor steer axle, per degree of RMS steer angle.

The responses were all, in general, very small -- no more than 2% of full scale on the data acquisition system. In some cases, the data must have been below the resolution of the transducers and system. It was not considered necessary to conduct a full frequency domain analysis, but the simple ratio of RMS response to RMS steer would be adequate to illustrate the principal differences between vehicles.

The results are summarized in Table 19, as RMS rear trailer lateral acceleration divided by RMS steer input.

Table 19/ Trailer Sway in Straight-Line Driving

Vehicle	Rear Trailer Lateral Acceleration (g/°)
45 ft Semi	0.63
A-Double	1.74
B-Double	1.49
C-Double	1.46
A-Triple	3.37
C-Traiple	2.05

The lateral acceleration ratios are roughly in proportion to the rearward amplifications of Table 17, though the similarity of the actual values is coincidental. The results for sway depend, in particular, upon the articulation measurements, which were very small. These results were questionable and are not presented. There is no doubt, however, that there was no perceptible sway to observers in a chase vehicle with the 45 ft (13.72 m) semi. For the doubles and the C-train triple, some other reference, such as a lane edge stripe, was necessary to observe the vehicle sway -- it was otherwise hardly perceptible. However, for the A-train triple, sway was continuous and strongly perceptible, with a distinct component of about 2 s period and 0.05 g lateral acceleration at the rear trailer.

5.10/ Steady Circular Turn

The objective of this test was to evaluate vehicle steady-state rollover characteristics to determine the high-speed offtracking of the vehicle and to examine the side loads exerted on the tractor by the trailers. A series of runs was made with the vehicle circumscribing a circle with a 50 m (164 ft) radius at a steady speed, according to the standard test procedure [1].

The 45 ft (13.72 m) semi experienced a smooth outrigger touchdown at 0.52 g in this test, as shown in Figure 32. The trailer was twisting due to the load distribution, and the entire vehicle may not have rolled over. The A-train double's rear trailer rolled over independently of the rest of the vehicle at a lateral acceleration of 0.53 g and caused the dolly to slide out. This was a rather violent response, unlike the smooth rollover of the 45 ft (13.72 m) semi and a similar A-train in an earlier test [11]. The B- and C-train doubles both had so much drag in this manoeuvre that speed dropped off significantly after they entered the circular turn. On both vehicles the outriggers of both trailers touched down at 0.49 g for the B-train and 0.54 g for the C-train. Whether these vehicles would actually have rolled over may be questionable. Certainly, all wheels except those of the tractor clearly lifted for the B-train (Figure 33), but speed was dropping off fast at this point, so it was difficult to decide exactly what would have happened. Both of these vehicles would roll over the entire vehicle, in contrast to the A-train double, which would only roll over the rear trailer. For both A- and C-train triples the low trailer centre of gravity previously mentioned and the 2.59 m (102 in) wheel track width elevated the roll

threshold above the threshold of lateral/directional stability. The rear trailer swung out on entry to the circular turn, and the driver steered out from the circle, at 0.50 g for the A-train and 0.46 g for the C-train. If the trailer centre of gravity had been higher, the A-train's rear trailer would undoubtedly have rolled over, and presumably the entire C-train triple vehicle would have rolled over. While rollover was the "expected" consequence of this test, the actual result illustrates that other modes of instability are possible, as seen in the lane change, discussed in Section 5.8, for these vehicles.

The 45 ft (13.72 m) semi and the three doubles all have suspensions of similar roll stiffness, axle loads, and centre of gravity heights. It is hardly surprising that they have similar roll characteristics. In a manoeuvre at the limits of stability in an A-train, the driver has little, if any, feel for the rear trailer's state, and that trailer can rollover while the rest of the vehicle remains upright. However, in the semi or either of the other two doubles, the driver can feel roll moment transmitted forward from the rear trailer and, knowing that the entire vehicle will rollover, may have an opportunity to stabilize the vehicle. Drivers would be expected to prefer the A-train, as the likelihood of death or serious injury in a heavy truck rollover is high. However, with the feel provided by a B- or C-train, it might be expected that the driver would respond to the vehicle and be better able to avoid the marginal situation. From this point of view, the B- or C-train double is preferred to the A-train.

A static tilt test was conducted on the 45 ft (13.72 m) semi and the three doubles. The two triples were too long to fit on the tilt table. The outer sections of the outrigger were removed for this test, which raised the centre of gravity of each trailer about 0.06 m (2.5 in) from the values quoted in Section 2. The table was tilted until a vehicle rollover condition was achieved, as indicated by the loads on critical high-side wheel pads becoming zero. For the A-train double the critical axles were those on the rear trailer only, as this trailer was free to roll independently of the rest of the vehicle as the dolly hitch offers no roll restraint. For the other three vehicles, all high-side wheel pad loads, except, possibly, those at the steer axle, were required to reach zero, as roll moment was transmitted between all vehicle units of these combinations. A typical rollover condition is shown in Figure 34, with the A-train double. The angles at which rollover occurred in the tilt test are compared in Table 20, with the peak lateral acceleration at which the vehicle unit rolled over in the steady circular turn. These

tilt angles include all appropriate corrections, discussed elsewhere [12].

Table 20/ Comparison of Roll Thresholds, Tilt Test and Steady Circular Turn

Vehicle	Tilt Angle (deg)	Tangent of Tilt Angle	Lateral Acceleration at Rollover in Steady Circular Turn (g)	Centre of Gravity Height Above Table (m)
45 ft Semi	28.4	0.54	0.52	1.78
A-Double	29.1	0.56	0.53	1.69
B-Double	26.9	0.51	0.49	1.75
C-Double	28.0	0.53	0.54	1.73

The agreement here seems quite good, but the data are sparse and are based on a single test in each case. It is, therefore, difficult to ascribe much significance to the differences.

The closeness of the tilt test results for these four vehicles bears out the observation that these vehicles all have similar suspensions, axle loads, and centre of gravity heights. Because their centres of gravity were quite low, it was necessary to make a very aggressive turn to achieve rollover: 0.5 g or higher would require a ramp advisory speed to be exceeded by 80% or more, which may be done in a car but is far beyond typical driving in a truck. The 1.75 m (70 in) centre of gravity height of Table 20 is typical of a load of steel or bricks. However, tankers, vans, and flatbeds of lumber can often have a centre of gravity more than 2.5 m (100 in) above the ground, which for the vehicles tested would reduce their rollover threshold to 0.3 g or so, a substantial decrease [17]. Such an elevated centre of gravity would have resulted in rollover of the triples in this test. It would also have resulted in rollover of all vehicles in the lane-change test (Section 5.8).

6/ DISCUSSION

Tests were conducted with the equipment as provided. No efforts were made to modify the equipment, except as required for testing, and these modifications did not affect vehicle operation. The outrigger assembly was additional to normal trailer equipment, and the characteristics of the trailers were, therefore, somewhat atypical, in both empty and loaded conditions. In both conditions, the centre of gravity was somewhat lower than normal because of the underslung outriggers.

The test program started in early June at Centralia, transferred to Blainville in August, and returned to Centralia at the end of November for two more weeks of testing. A test program of such duration encountered a variety of weather conditions. The summer months, with air temperatures of 25 to 30°C, resulted in high-friction surface temperatures up to 55°C and low-friction surface temperatures about the same as the air temperature. However, in the final four weeks, air temperatures were -3 to +5°C, and surface temperatures were about 3 to 5°C. The low-friction surface was less slippery in cold conditions. It also appeared less slippery to the test driver than during a previous series of A- and C-train tests [11], though those tests used different tires. The B-train and A- and C-train triples were tested in similar warm conditions, whereas the 45 ft (13.72 m) semi and A- and C-train doubles were tested in cold conditions. While temperature may affect tire traction characteristics, there should be little effect for comparisons within these groups.

Tires were installed new on the Freightliner at the start of the test program and were replaced once when half the usable tread had worn. Tires were installed new on each trailer and dolly. The C-triple was tested after the A-triple and used the same trailers. The C-double was tested after the A-double and also used the same trailers. When the tires were used for the second series of tests, they could still be described as "nearly new" and without evident unusual wear patterns.

It is not possible to make any meaningful remarks on the effect these factors might have had on the results, except for centre of gravity height, which has been mentioned already where it may have affected the results. The results presented pertain to the particular vehicles tested, and results different in some respects might be obtained for other vehicles at another time.

The test program was the largest undertaken by the ministry, and it was planned with the expectation that there would be delays. The expectation was fulfilled, though the delays were unscheduled. As autumn was trying to become winter, there were often extended periods when such inclement weather as rain, ice pellets, and snow prevented testing. Some time was lost because contracted work took longer than promised. Various pieces of equipment failed at various times, requiring repair, replacement from spares, or a change in the test sequence. Fortunately, no unduplicated piece of equipment failed and caused an extended delay. Finally, telemetry dropouts wasted many runs at Blainville. The source of the dropouts could never be established because the pattern changed with time and was not responsive to changes in transmitter or receiver antennae, ground station location, signal levels, or a number of other variables. As a consequence of these delays, tests on vehicles were done with varying depth to maintain schedule. Some were exhaustive, but others only completed the test objective. Only one test was omitted, the lane change on the A-train double, and this was done to maintain schedule only because the same test had previously been conducted with an almost identical vehicle [11].

The 45 ft semi was considered an easy vehicle to drive by the test driver. It tracked well, manoeuvred well, and was very stable. It just took more space to turn than the three doubles, due to the trailer length. The test driver also considered the A-train double an easy vehicle to manoeuvre and drive, particularly in the evasive manoeuvre on the low-friction surface. The trailers had little influence on vehicle handling in this case, whereas the trailers of both B- and C-train doubles were pushing the tractor through the return to the original lane. The tendency to push was also noticeable on the high-friction surface, particularly in the steady circular turn, where simply following the turn required considerably greater effort in the B- and C-trains than in the A-train. It was of interest, though, that the driver was very satisfied with the handling of the C-train double on the highway in snow and ice when the vehicle was being returned from Blainville to Centralia. The short trailer wheelbase and single axle made the A-train triple easy to manoeuvre in both low-speed turns and dynamic tests, as the trailer imposed rather modest forces on the tractor. It was also particularly easy in the evasive manoeuvre on a low-friction surface, where the rear two trailers and dollies appeared to slide through the gates. However, because it was so responsive it was very easy for the driver to create a trailer swing situation, and this would have been a rollover situation with a higher trailer centre of gravity. The driver had no feedback of

second- or third-trailer response once a manoeuvre had started, because the A-dolly hitch does not transmit trailer roll moment forward. The responsiveness of this vehicle in normal driving, particularly when empty, was a concern because rough roads excited considerable trailer sway. Even hauling two trailers to the test site on delivery was not a pleasant experience. By contrast, the C-train triple was rather stable, but again it tended to push the tractor in manoeuvres. With regard to the C-trains, the driver felt that the Sauer axle was preferable to the axle tested previously [11] because the force required to break out the self-steering mechanism was lower, so the axle appeared to steer almost continuously in a dynamic manoeuvre. In the earlier test, the steer would break out suddenly and unexpectedly during the manoeuvre, affecting performance of the manoeuvre by the driver.

In absolute terms there is no question that the 5-axle 45 ft (13.72 m) semi was the most stable of the six baseline vehicles. This is attributable simply to its single point of articulation and the long wheelbase of the trailer. However, this is a utility vehicle and is not the vehicle of choice for heavy-haul applications, where double trailer combinations with more than five axles can carry higher gross weights. There is also no question that the B- or C-train doubles tested were more stable than the A-train double, simply because these two vehicles have one less point of articulation. However, the issue was by no means clear-cut. In the evasive manoeuvre on the wet low-friction surface, the A-train double might be judged to have performed better than the B- or C-train. It was certainly the easiest for the driver to put through the course, but this was because the driver had no feel for second trailer response which is available with the other two configurations. However, from previous experience [11], the dolly jackknife/trailer swing mode of loss of control of the A-train is judged potentially more hazardous to other road users than the loss of tractor control that is most apparent with the B- or C-trains. On the high friction surface the A-train had the highest rearward amplification. Because all three vehicles had similar roll thresholds, the A-train double is the most vulnerable to rear trailer swing or rollover in a dynamic manoeuvre. Again, because of a lack of feedback from the rear trailer to the driver, it is more likely that the driver of an A-train will approach the point where loss of control is likely than will the driver of a B-train or the corresponding C-train.

7/ COMPUTER SIMULATION

The University of Michigan Transportation Research Institute (UMTRI) yaw/roll model [18] was installed on the HP-1000 computer used in the ground station for data processing. The program was extended to simulate a triple trailer combination and was updated to include an improved B-dolly model developed by UMTRI, so that all vehicles tested could be simulated with the same program. Details of the internal computation were also modified to achieve run times no more than 25% the duration of those for the original program, and in most cases much less.

The properties of vehicle unit suspensions were available from parametric measurements made by UMTRI, as were tire properties [19]. The geometric properties of vehicles were measured, and mass properties were determined by a process of weighing and calculation. By this means, data sets were prepared that were representative of the vehicles as they were actually tested.

The program was also modified to read the steer input measured during a test run and the initial conditions for some other model degrees of freedom from the test data. It then integrated the equations of motion, computed responses of interest at the measurement locations on the test vehicle, and stored those responses in a data file having the same format as that containing the responses measured in the test. The test and simulation results could, then, be directly compared.

This test program consisted of standardized tests of nine vehicles of different configurations. It provided an opportunity to exercise computer simulation techniques over a wide range of cases. The objective was to demonstrate that computer simulation could represent a vehicle's response in a specific manoeuvre and the trend in response characteristics over a range of manoeuvres. The program data were set up to be as representative as possible of the actual vehicle tested, using generic data where directly measured data were not available. This work was not a validation of the computer model.

Computer simulation was conducted for all vehicles in the loaded condition for the following tests on a high-friction surface:

1/ sinusoidal steer
2/ lane change
3/ steady circular turn

All vehicles showed good agreement between the simulation and test results in the sinusoidal steer. However, it was found necessary to modify the tractor drive axle tire characteristics for the B-train simulation to match the test results as well as the other five vehicles did. This modification was considered acceptable because no measured data were available for these tires, so essentially the simulation provided a tool whereby the tire characteristics could be approximated. This tire modification was found essential for all vehicles if the simulation was to match the test results in the steady circular turn.

This work showed that the computer simulation could produce quite reasonable agreement with test results for a range of vehicle configurations and conditions, both for individual runs and as a trend over a number of runs. This agreement was obtained using generic tire and suspension data with accurate geometric and mass data. Better agreement with individual runs could, perhaps, have been achieved by "tuning" the data. However, since many of the deviations were of the same order as differences between test runs, such effort did not appear warranted.

A detailed summary of this work is presented elsewhere [10].

8/ CONCLUSIONS

The CCMTA/RTAC Vehicle Weights and Dimensions Study selected a baseline vehicle to represent each of six major truck configurations: the tractor-trailer; A-, B- and C-train doubles; and A- and C-train triples. The Ontario Ministry of Transportation and Communications subjected each of these baseline vehicles to a standard series of tests for turning; the air brake system; lateral/directional and roll stability; trailer sway; and a demonstration of straight-line braking.

Vehicle turning performance depends primarily on trailer length and the number of trailers. It is not strongly dependent on the method of hitching. As trailer length or number of trailers increases, so does the space required to make turns.

Air brake system performance depends on the number of vehicle units and selection and installation of components.

Lateral/directional stability is strongly dependent upon vehicle configuration. The semi was the most stable, doubles were more stable than triples of similar configuration, and B- or C-trains were more stable than the A-train. This ranking follows the number of articulation points -- the more articulation points, the lower the stability.

Static roll stability is essentially independent of vehicle configuration where vehicles have the same suspension, axle load, and centre of gravity height.

An extensive computer simulation showed that responses of all vehicles could be predicted quite well, both for individual runs and as a trend over a number of runs.

The specific results presented here apply to the vehicles tested for the particular test conditions. Results different in some respects might be expected for other vehicles or test conditions.

9/ REFERENCES

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Figure 1/ 45 ft Semi, View of Vehicle

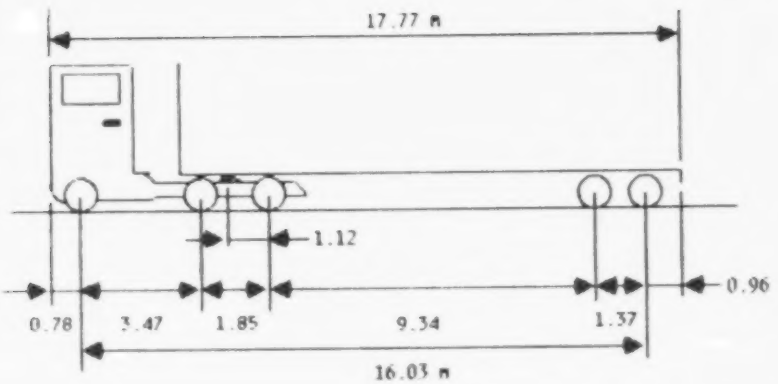


Figure 2/ 45 ft Semi, Vehicle Dimensions

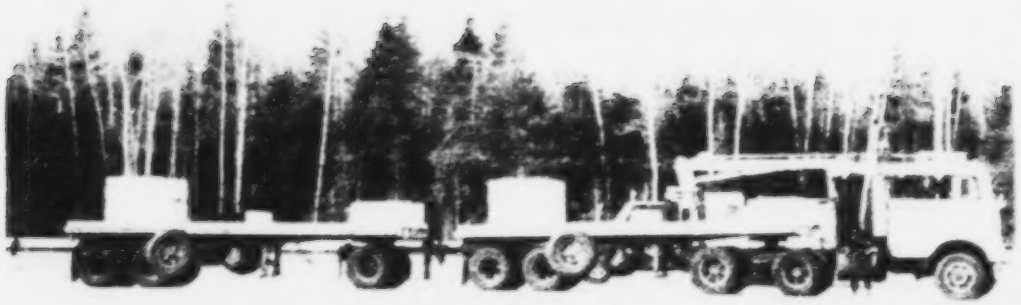


Figure 3/ A-Train Double, View of Vehicle

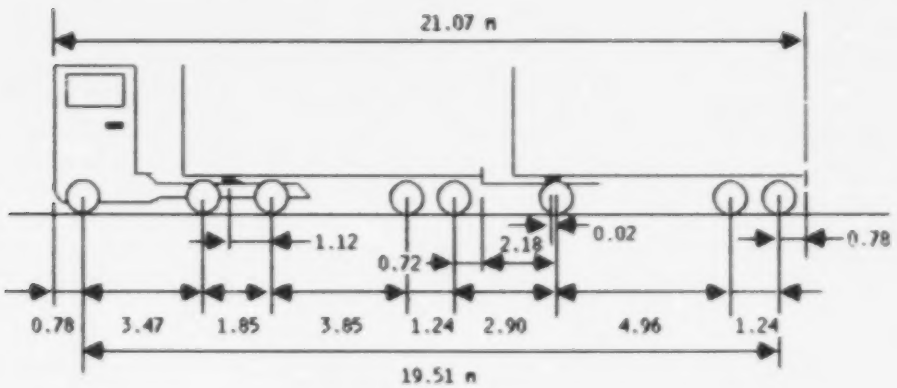


Figure 4/ A-Train Double, Vehicle Dimensions

Figure 5/ B-Train Double, View of Vehicle

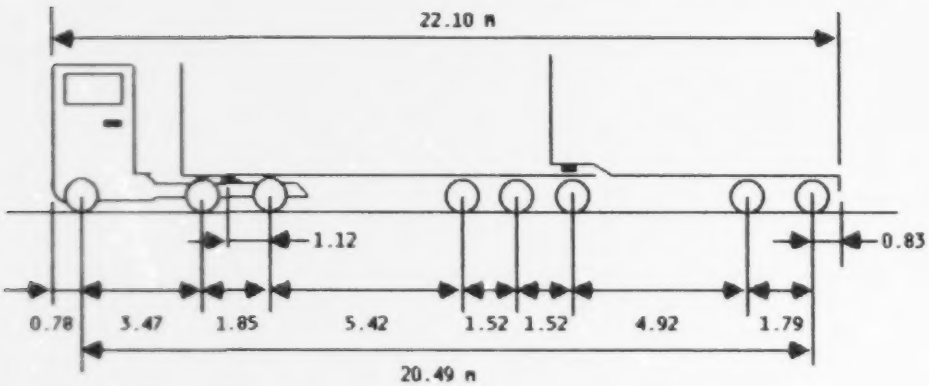


Figure 6/ B-Train Double, Vehicle Dimensions

Figure 7/ C-Train Double, View of Vehicle

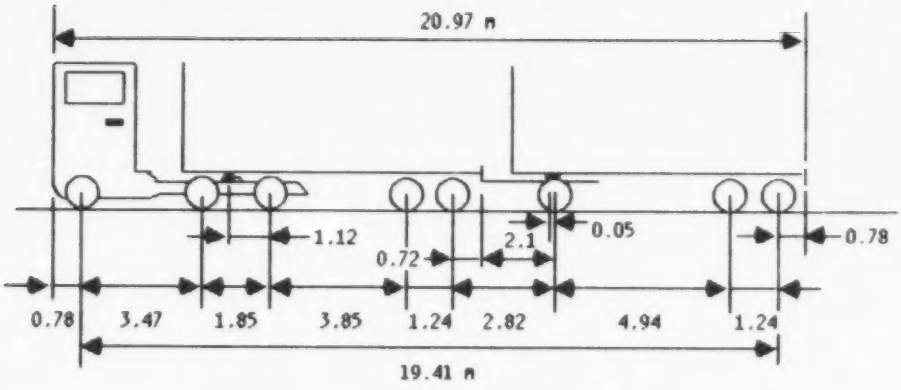


Figure 8/ C-Train Double, Vehicle Dimensions

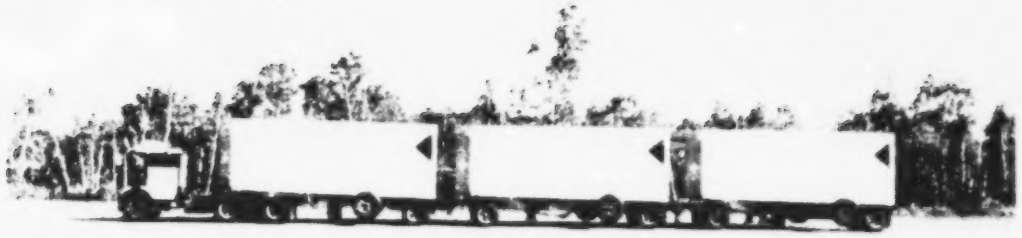


Figure 9/ A-Train Triple, View of Vehicle

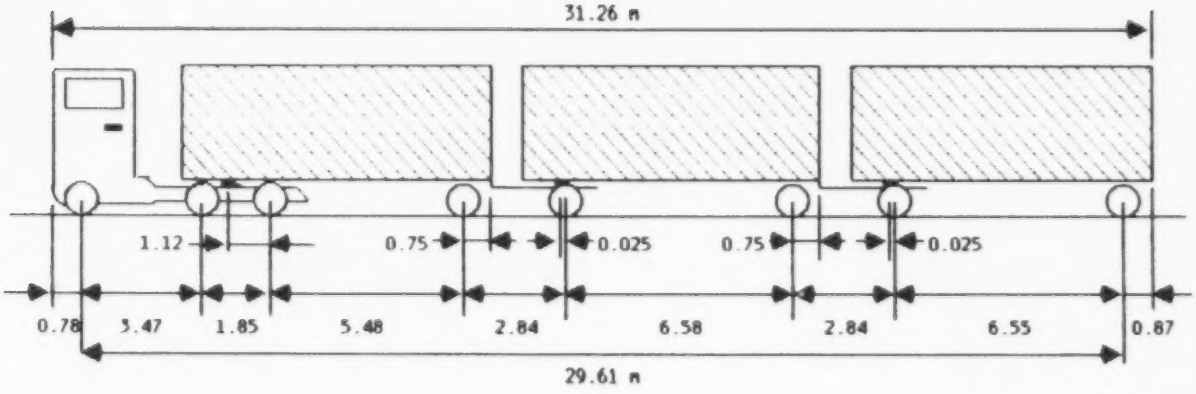


Figure 10/ A-Train Triple, Vehicle Dimensions

Figure 11/ C-Train Triple, View of Vehicle

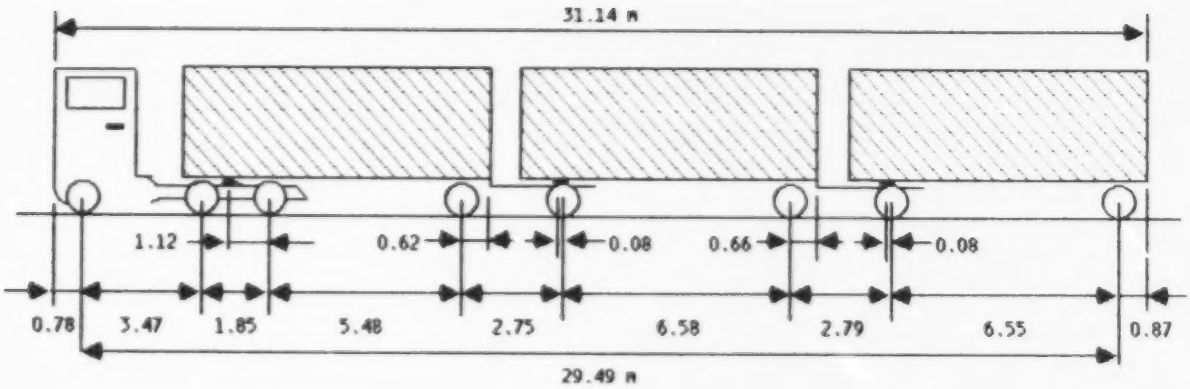


Figure 12/ C-Train Triple, Vehicle Dimensions

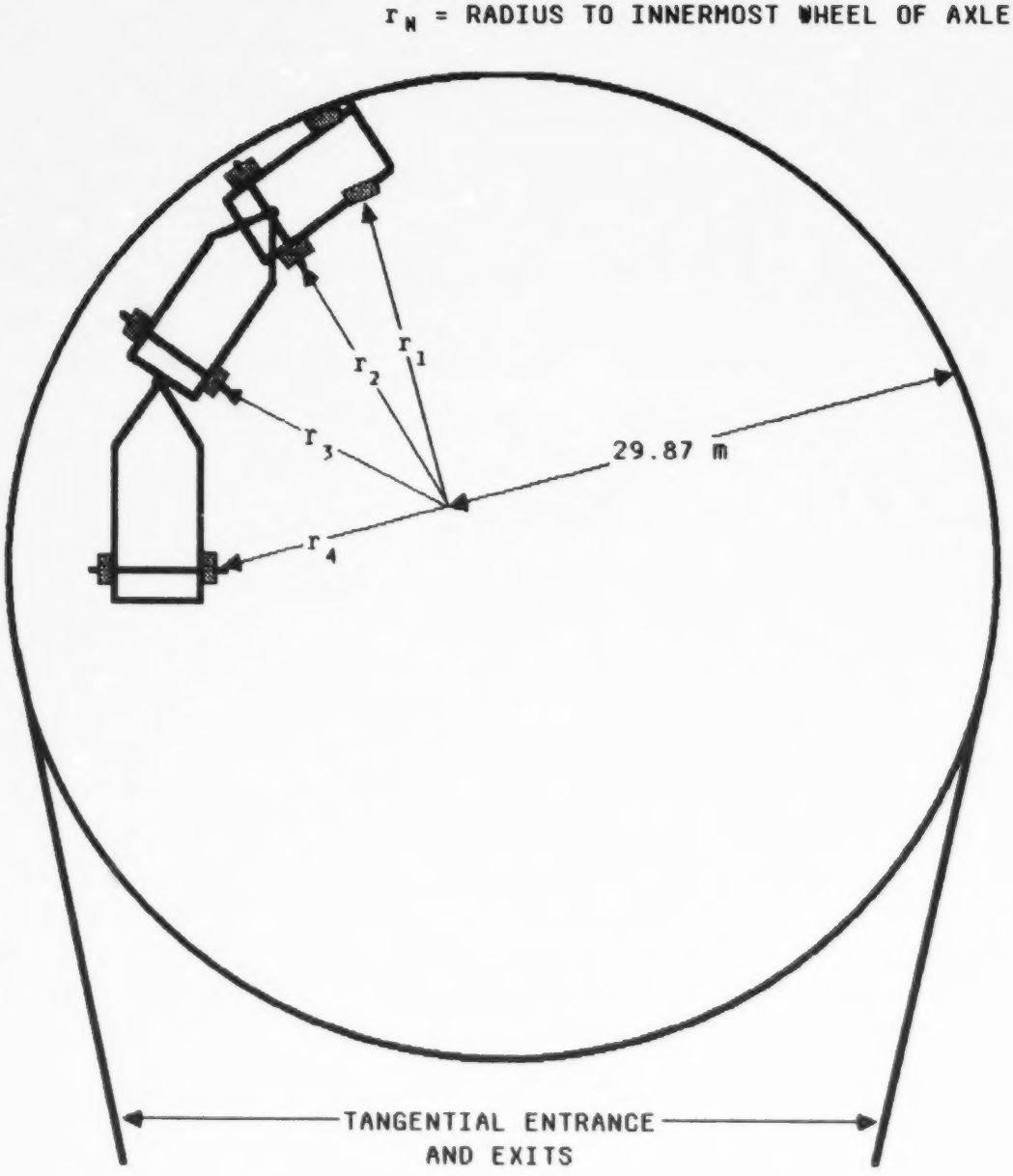


Figure 13/ Offtracking Course

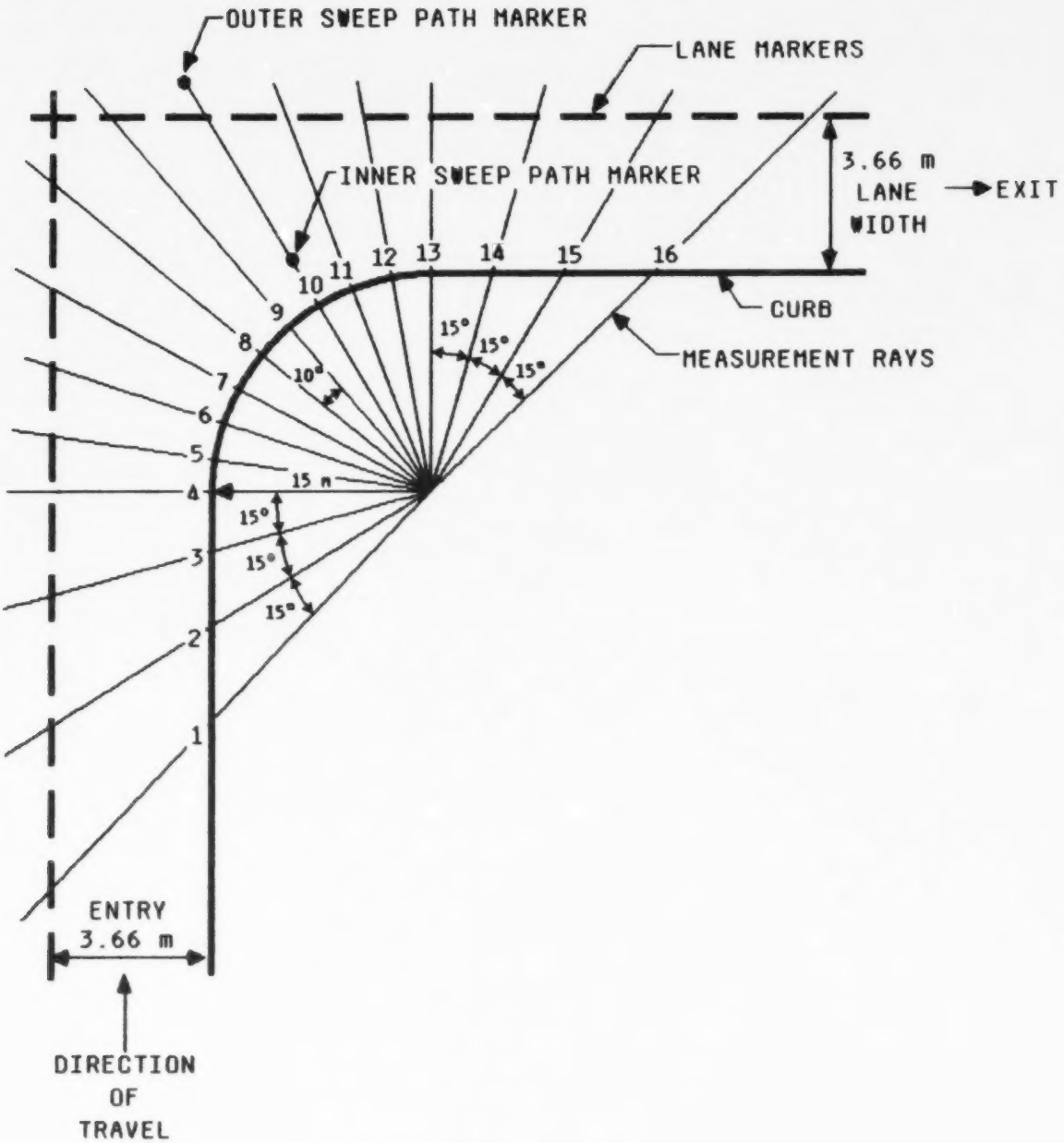
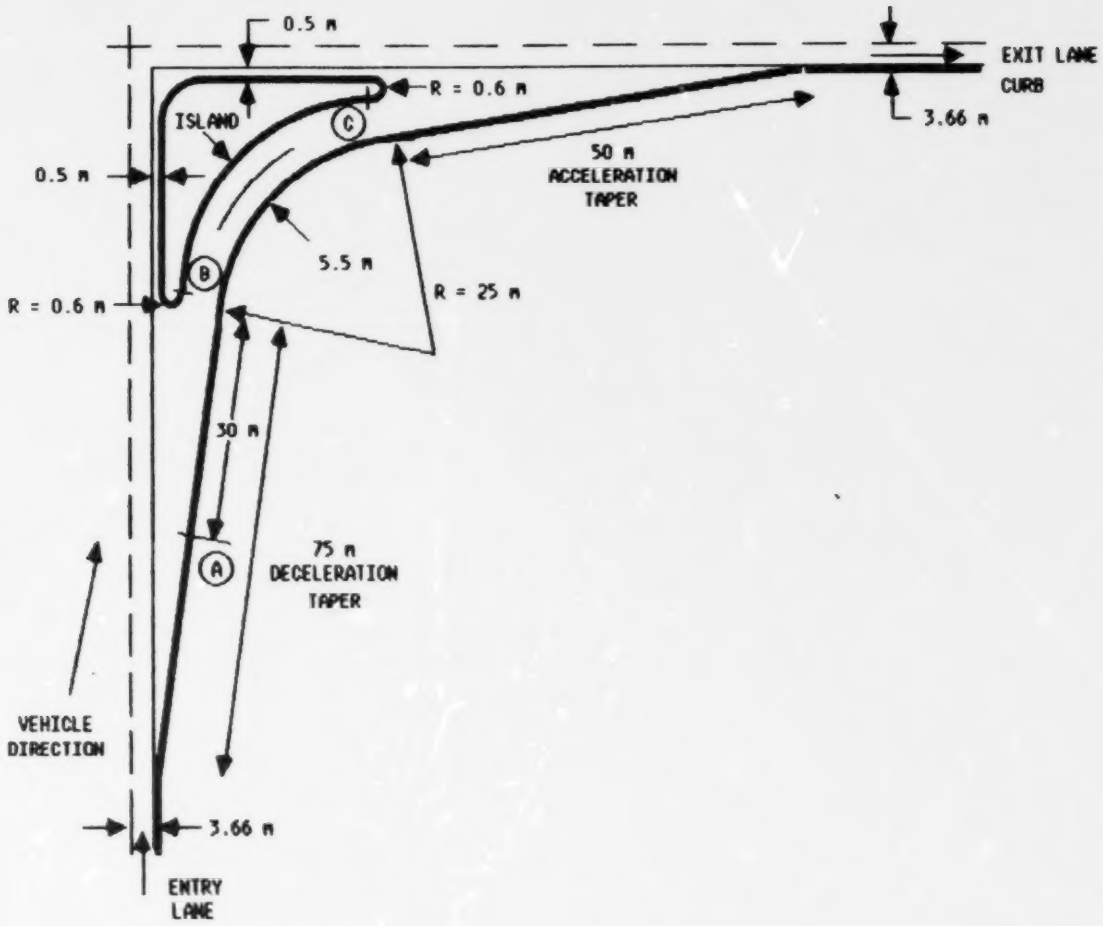
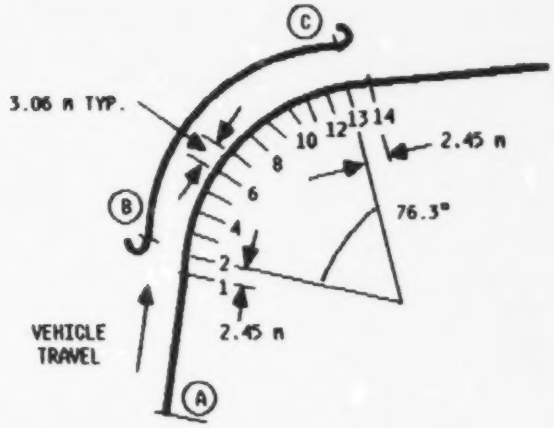


Figure 14/ Right-Hand Turn Course



(a) Geometry



(b) Measurement Reference Points

Figure 15/ Channelized Right-Turn Course

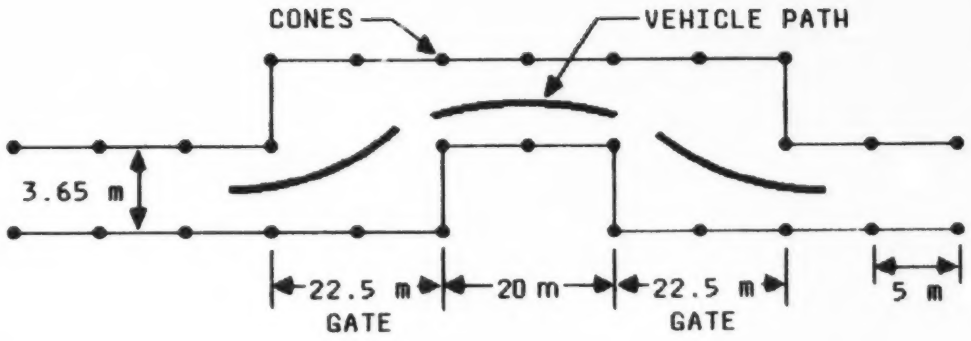


Figure 16/ Evasive Manoeuvre Course

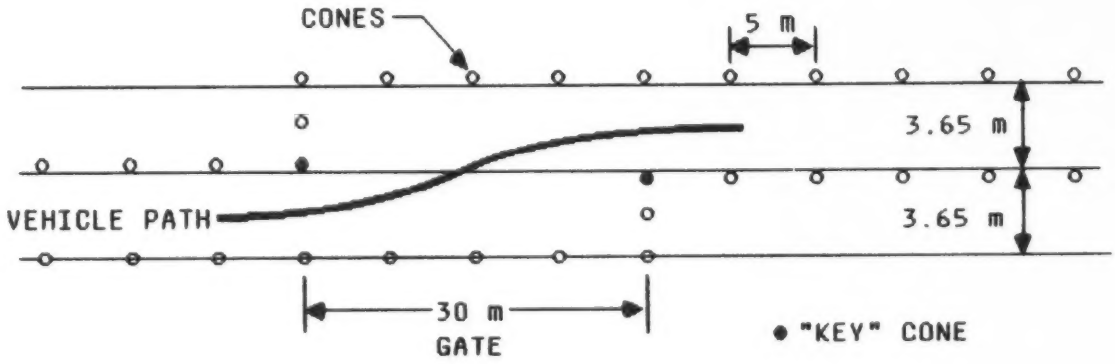


Figure 17/ Lane-Change Manoeuvre Course

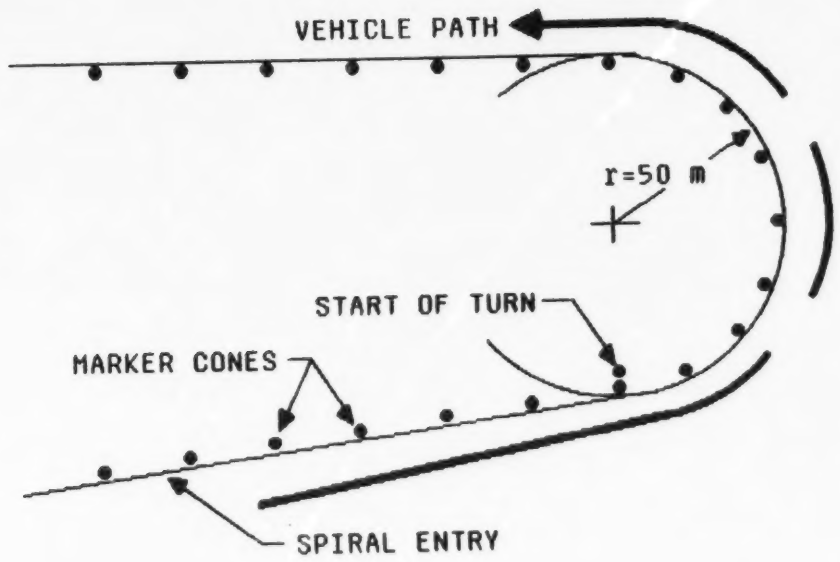


Figure 18/ Steady Circular Turn Course

Figure 19/ C-Train Double, Clockwise Final Offtracking

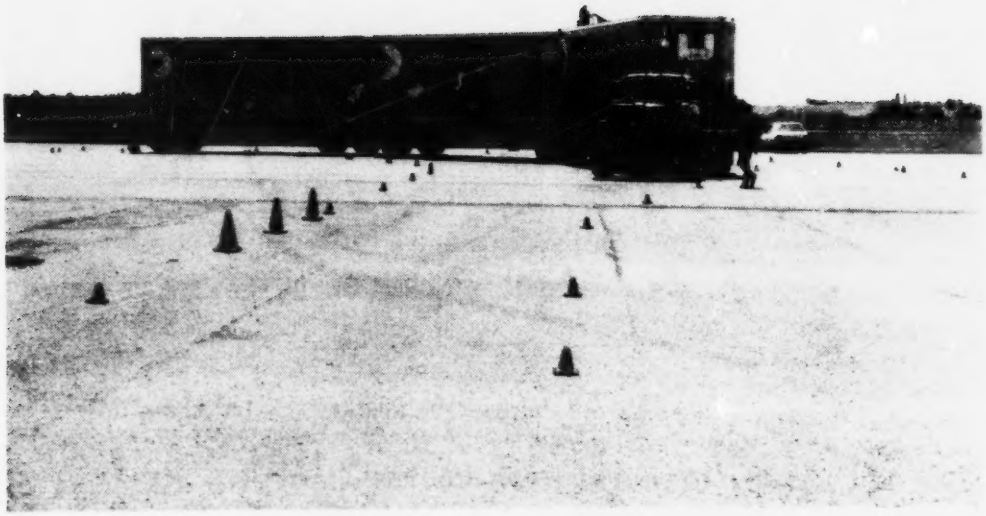


Figure 20/ C-Train Triple, Right-Hand Turn

Figure 21/ C-Train Triple, Channelized Right Turn

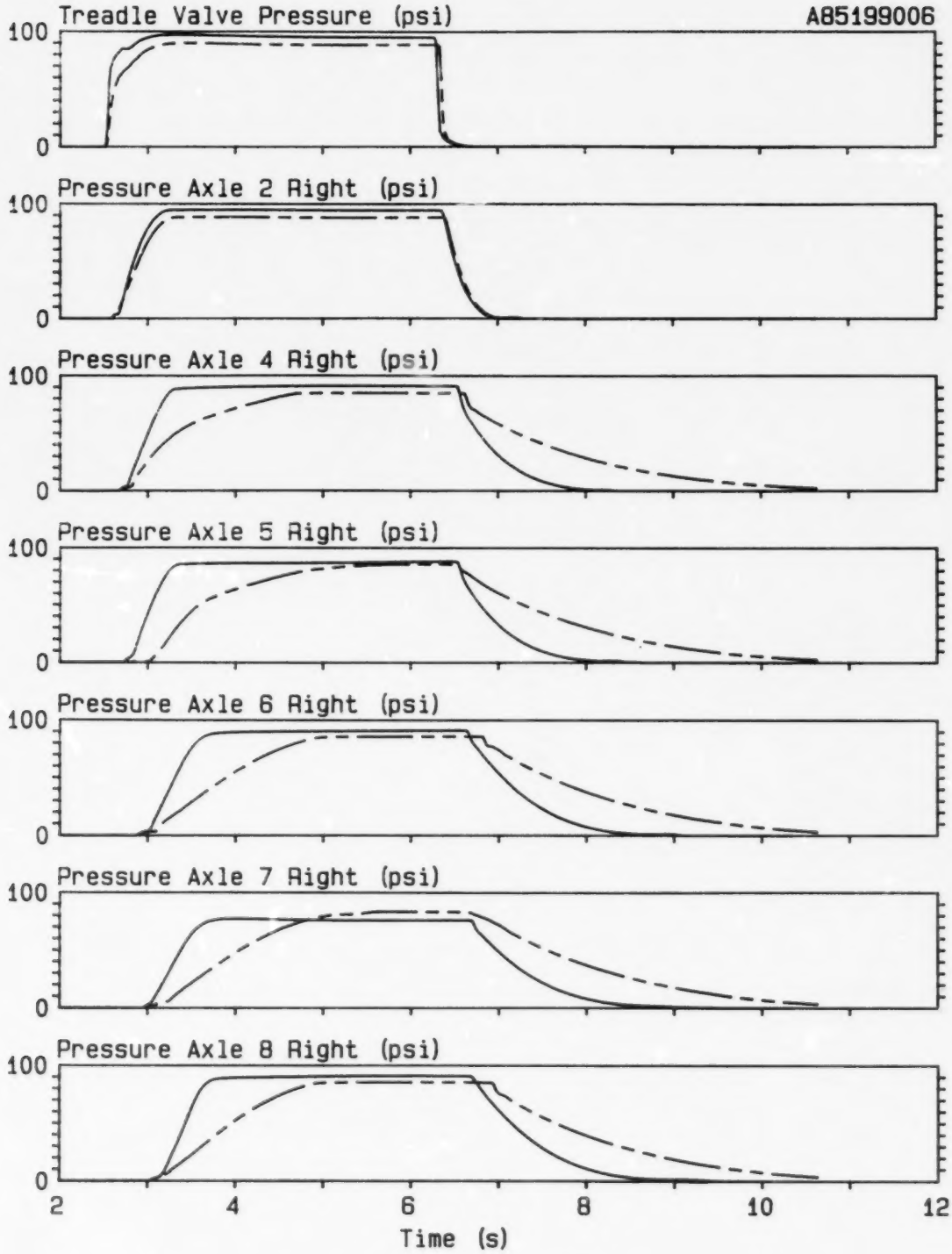


Figure 22/ A-Train and C-Train Triples,
Air Brake Application and Release

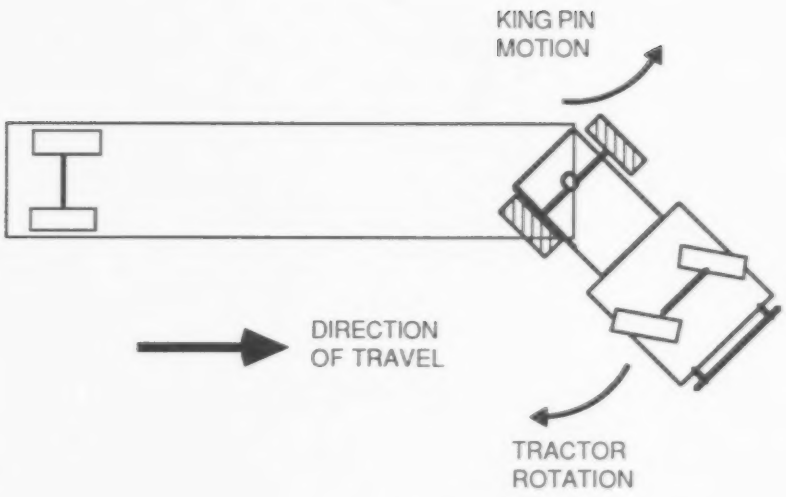


Figure 23/ Tractor Jackknife

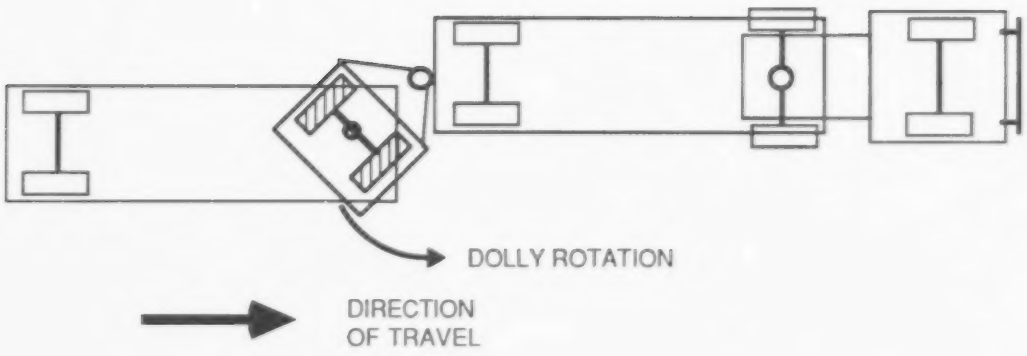


Figure 24/ A-Train Dolly Jackknife

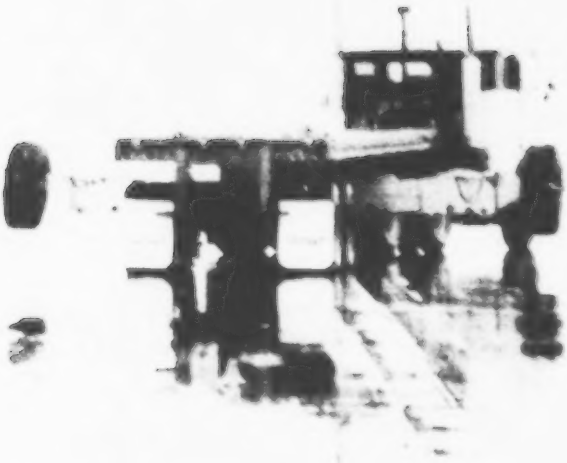


Figure 25/ 45 ft Semi, Straight-Line Braking

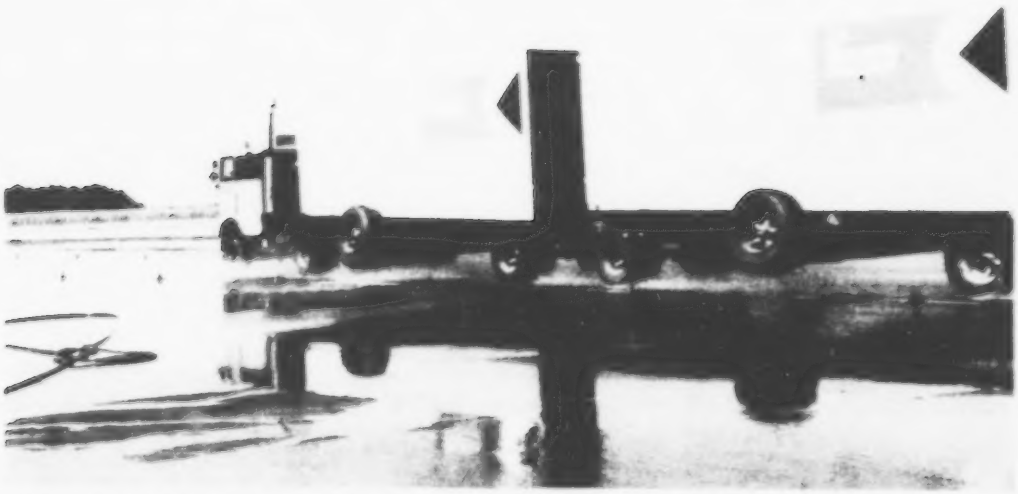


Figure 26/ A-Train Triple, Evasive Manoeuvre

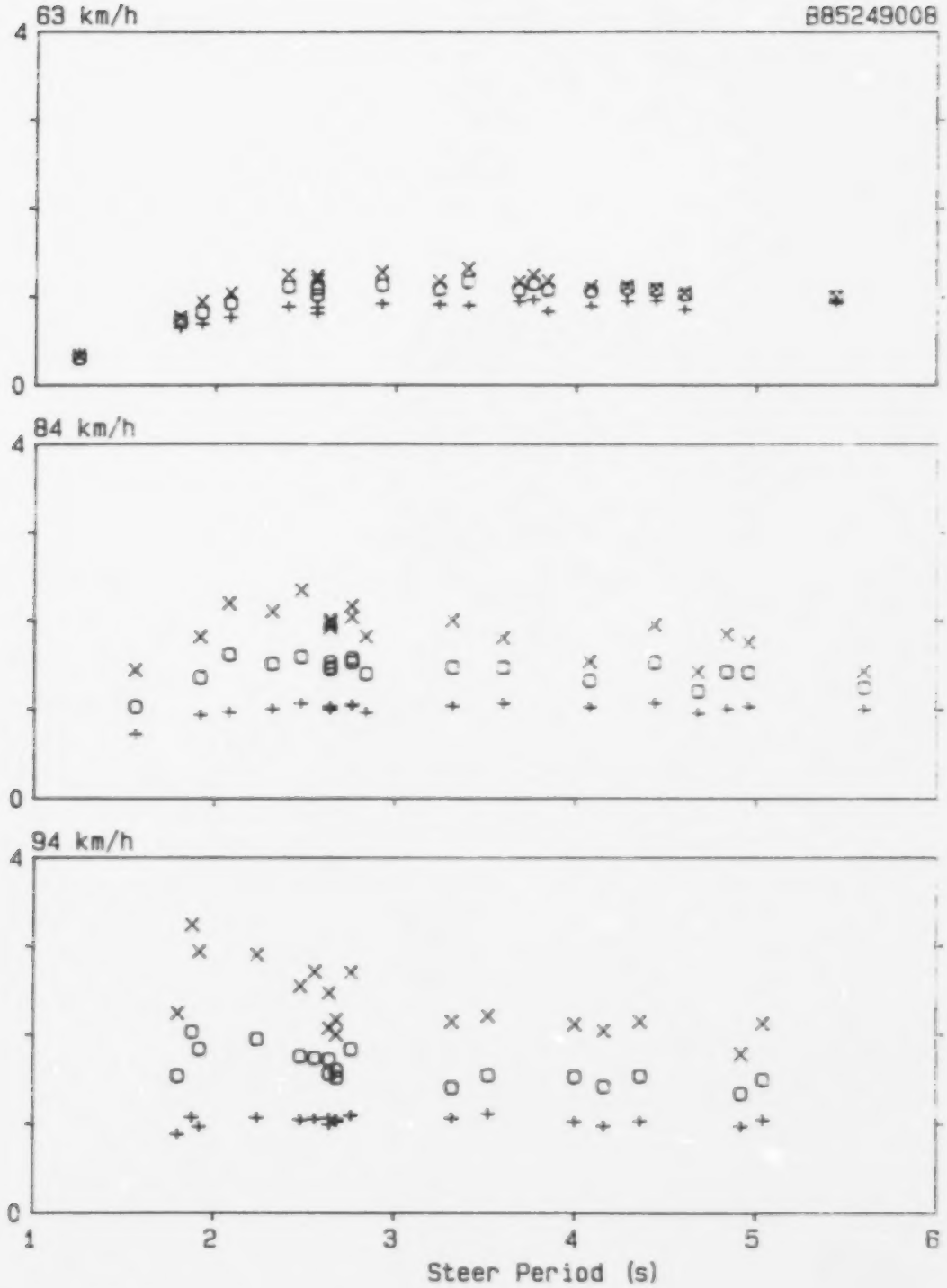


Figure 27/ A-Train Triple,

Rearward Amplification of Lateral Acceleration

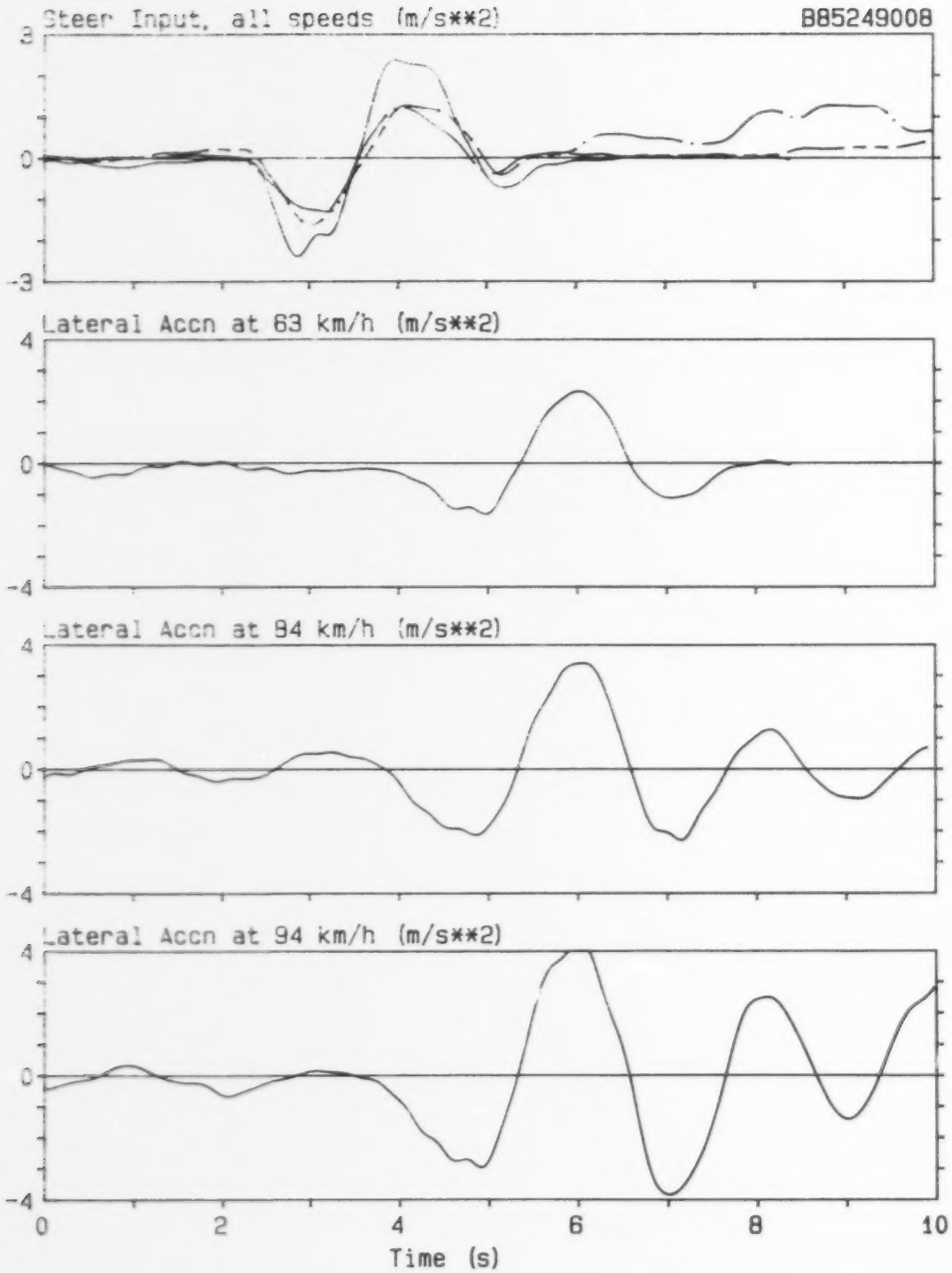


Figure 28/ A-Train Triple, Sinusoidal Steer,

Rear Trailer Lateral Acceleration at Three Speeds

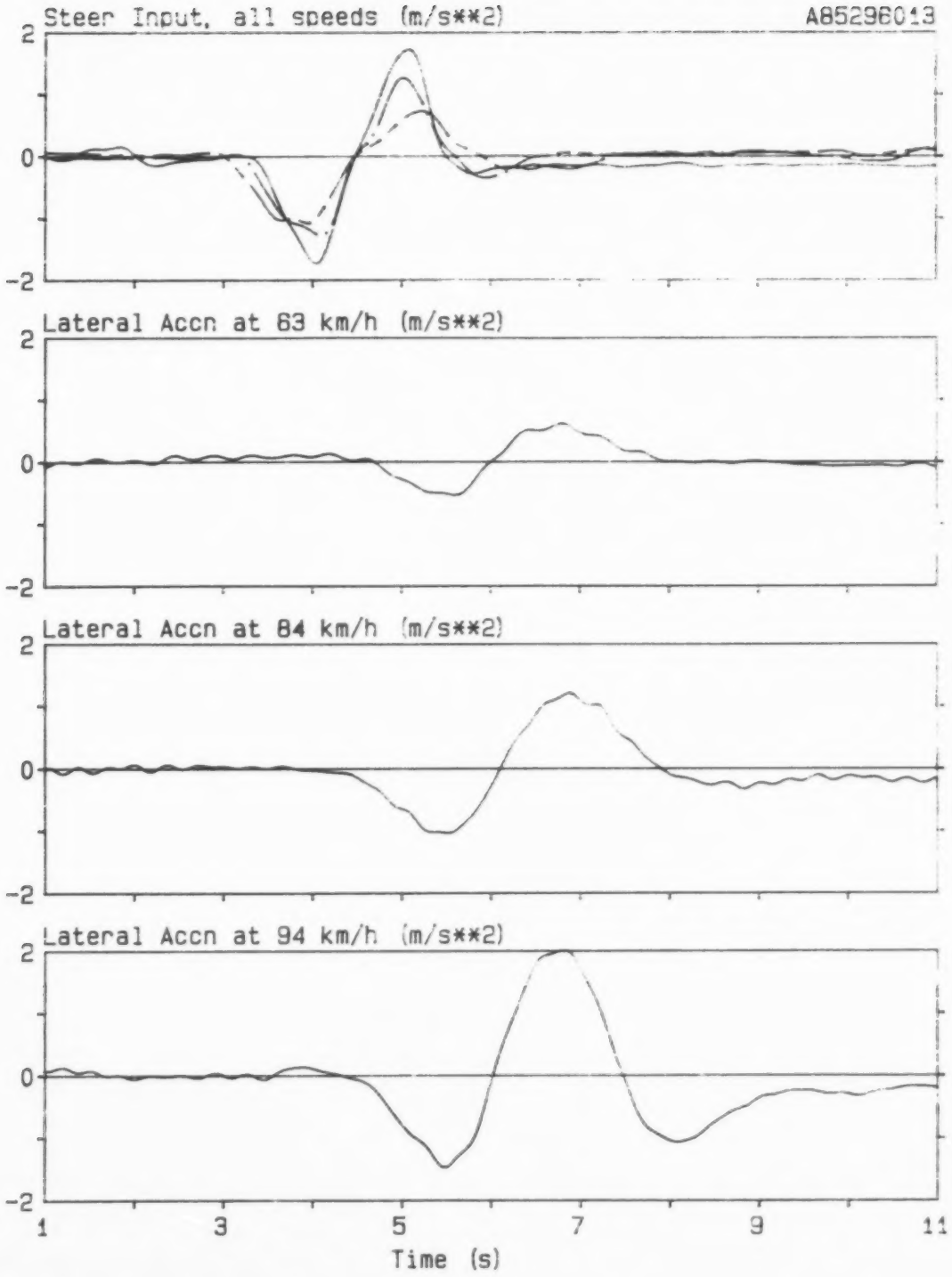


Figure 29/ C-Train Triple, Sinusoidal Steer,

Rear Trailer Lateral Acceleration at Three Speeds

Figure 30/ B-Train Double, Lane Change

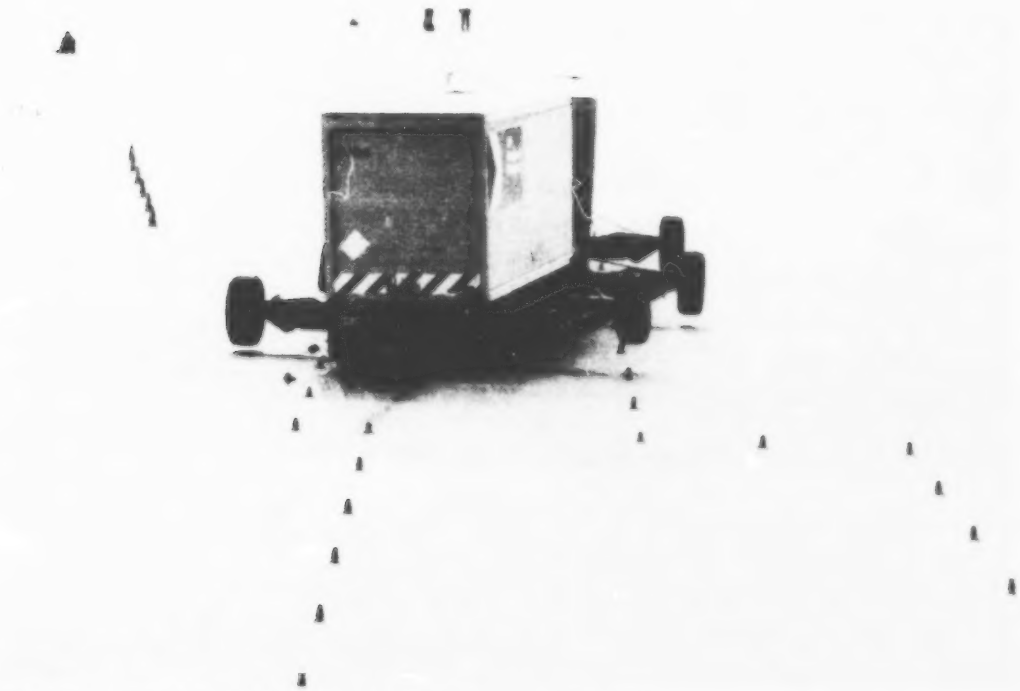


Figure 31/ A-Train Triple, Lane Change

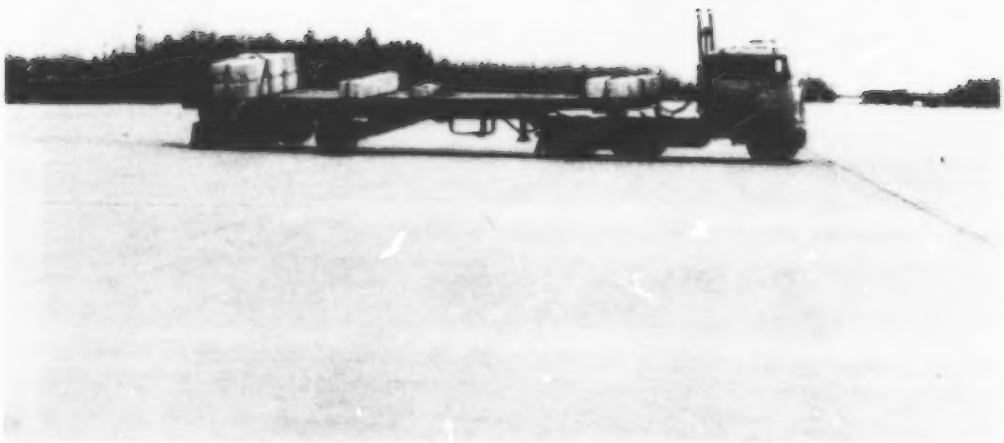


Figure 32/ 45 ft Semi, Steady Circular Turn

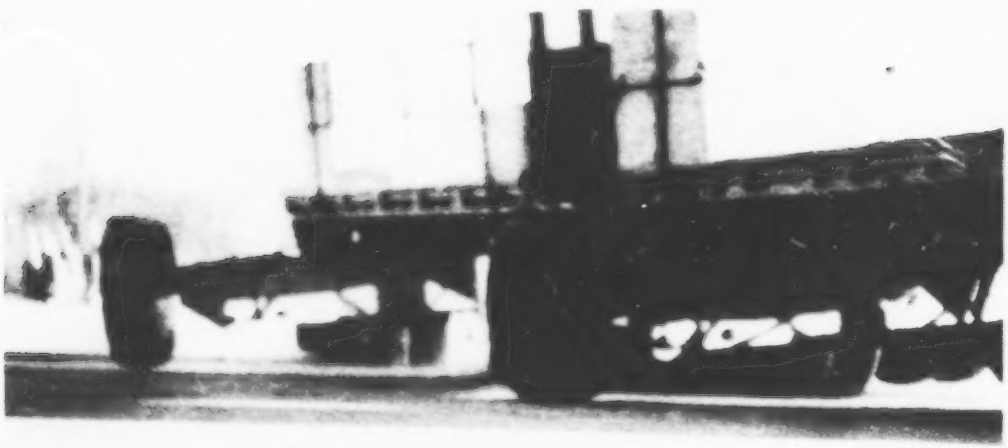


Figure 33/ B-Train Double, Steady Circular Turn

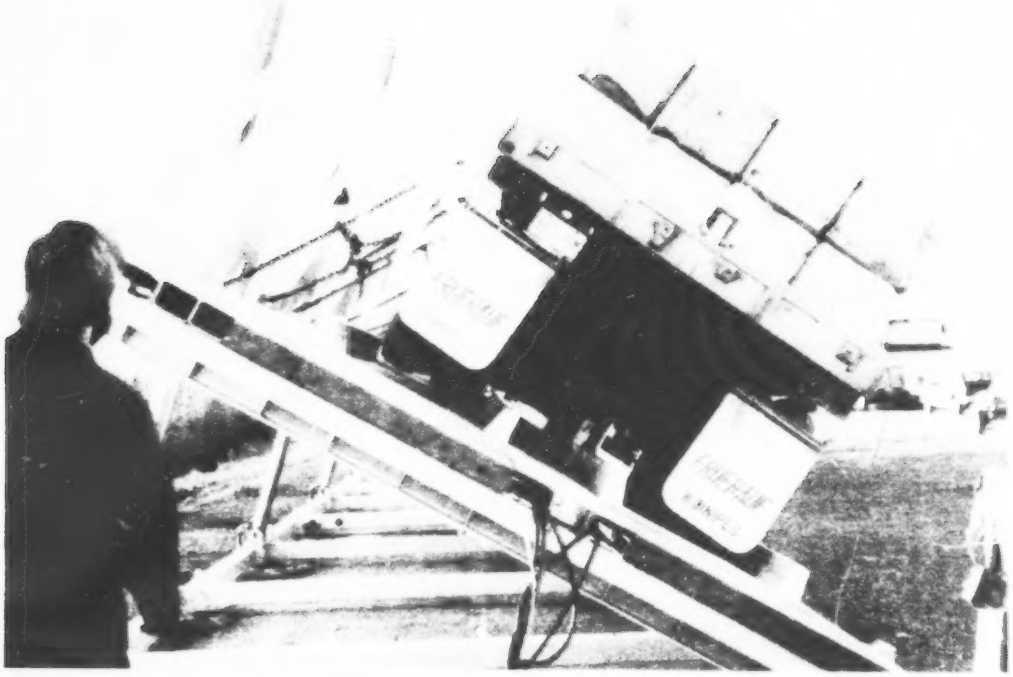


Figure 34/ A-Train Double, Tilt Test